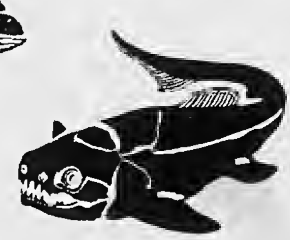
Journal of the Royal Society of Western Australia

ISSN 0035-922X

CONTENTS

Volume 96 Part 1
July 2013



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To promote and foster science in Western Australia

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The Journal of the Royal Society of Western Australia was first published in 1915. Its circulation exceeds 650 copies. Nearly 100 of these are distributed to institutions or societies elsewhere in Australia. A further 300 copies circulate to more than 40 countries. The Society also has over 350 personal members, most of whom are scientists working in Western Australia. The Journal is indexed and abstracted internationally.

Cover design: The four subjects symbolize the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Jan Taylor). The Gogo Fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

Plasma physics: an introductory survey

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This paper describes what plasmas are, why their study is essential to our understanding of the universe, how plasma physics is applied to many scientific and technological areas of development, and how it possibly could provide the solution to the world's energy problems. In addition, the paper will briefly describe Australia's involvement in this research and development area.

KEYWORDS: **fusion energy, fusion reactions, nucleosynthesis, physics, plasmas.**

WHAT IS A PLASMA?

A plasma is an ionised gas in which the nearest neighbour interactions between the electrically-charged constituents (negatively-charged electrons and positively-charged ions, which are in equal numbers so as to maintain overall electrical neutrality) is dominated by the long-range interactions of many 'distant' particles. In fact, many plasmas contain a significant number of un-ionised neutral atoms, but the long-range interactions dominate.

The force (F) between isolated point electrical charges e_1 and e_2, which are separated by a distance r is

$$F = (e_1 e_2)/(4\pi\varepsilon_0 r^2) \qquad (1)$$

where ε_0 is the permittivity of a vacuum. This is the so-called Coulomb interaction, and because it falls off relatively slowly with distance r, is a 'long-range' one compared to the shorter range forces between the particles which are constituents of the three other forms of matter—solid, liquid and gas. A plasma has been termed 'the fourth state of matter', because it has properties which are quite distinctive.

As electrically-charged particles are constituents of a plasma, the plasma can conduct electrical currents, it can be influenced by electric and magnetic fields, and currents flowing in the plasma generate magnetic fields. Plasma can support a whole range of wave motions.

In fact, the above (classical) definition of plasma has been extended to other situations where plasma properties can still be found, e.g. non-electrically neutral situations.

BRIEF HISTORY OF PLASMA PHYSICS

Plasma was first identified as a 'different' state of matter in the study of low-density ionised gases, which were formed in electrical discharge tubes (Crookes 1879). The term 'plasma' was introduced by Langmuir (1928) and Tonks &Langmuir (1929) in connection with their studies of oscillations of ionised gases. Such oscillations (which today we refer to as plasma oscillations) are due to the strong restoring electrical forces that act whenever there are charge separations, as can occur as a result of thermal fluctuations.

Why the term 'plasma' was used is unclear. One explanation does involve the similarity with blood plasma (both carry particles), while another explanation refers to the Greek word meaning 'anything moulded or formed', since plasma usually moulds itself to the shape of its container. Plasma physicists have, ever since, had to clarify this issue, and in most cases, to express an ignorance of the properties of blood plasma!

In 1920, A S Eddington realised that from atomic mass determinations made by F W Aston it is possible that hydrogen can be converted to helium (by the fusion or joining together of the hydrogen nuclei) under the right conditions, and that this could be the origin of the source of energy for all stars, in particular the sun. G Gamow, in 1928 derived (using quantum mechanics) the formula for the fusion of two nuclei with the associated release of energy (as matter and energy are equivalent according to Einstein). R Atkinson and F G Houtermans (in 1929) then used Gamow's results to calculate the rate of energy production arising from thermonuclear fusion reactions in hydrogen plasma in stellar cores. H Bethe (in 1939), elucidated the processes whereby the energy of stars is produced, for which he received the 1967 Nobel Prize in Physics. This theory worked well for stars with masses up to about the mass of the sun. In 1938, C F von Weizsecker identified processes which were important in more massive stars. The study of the creation of heavier nuclei in such fusion processes was initiated by F Hoyle in 1946. This interesting story is described in more detail in the history section of the Wikipedia article on nucleosynthesis (http://en.wikipedia.org/wiki/Stellar_nucleosynthesis). Nucleosynthesis is the formation of the chemical elements by nuclear reactions occurring in the cores of stars. Fusion is thus a fundamental process in the establishment and maintenance of the universe.

The first fusion reactions performed in the laboratory were carried out by the 'fathers of fusion' M Oliphant, P Harteck and E Rutherford in the early 1930s (Oliphant *et al.*1934).

ABUNDANCE OF PLASMA

Plasma is the most common state of visible matter in the entire universe. It is estimated that over 99% of the visible matter in the universe is in the plasma state (Figure 1a) e.g. intergalactic medium, interstellar medium, and the solar system [the sun (Figure 1b), the solar wind and the

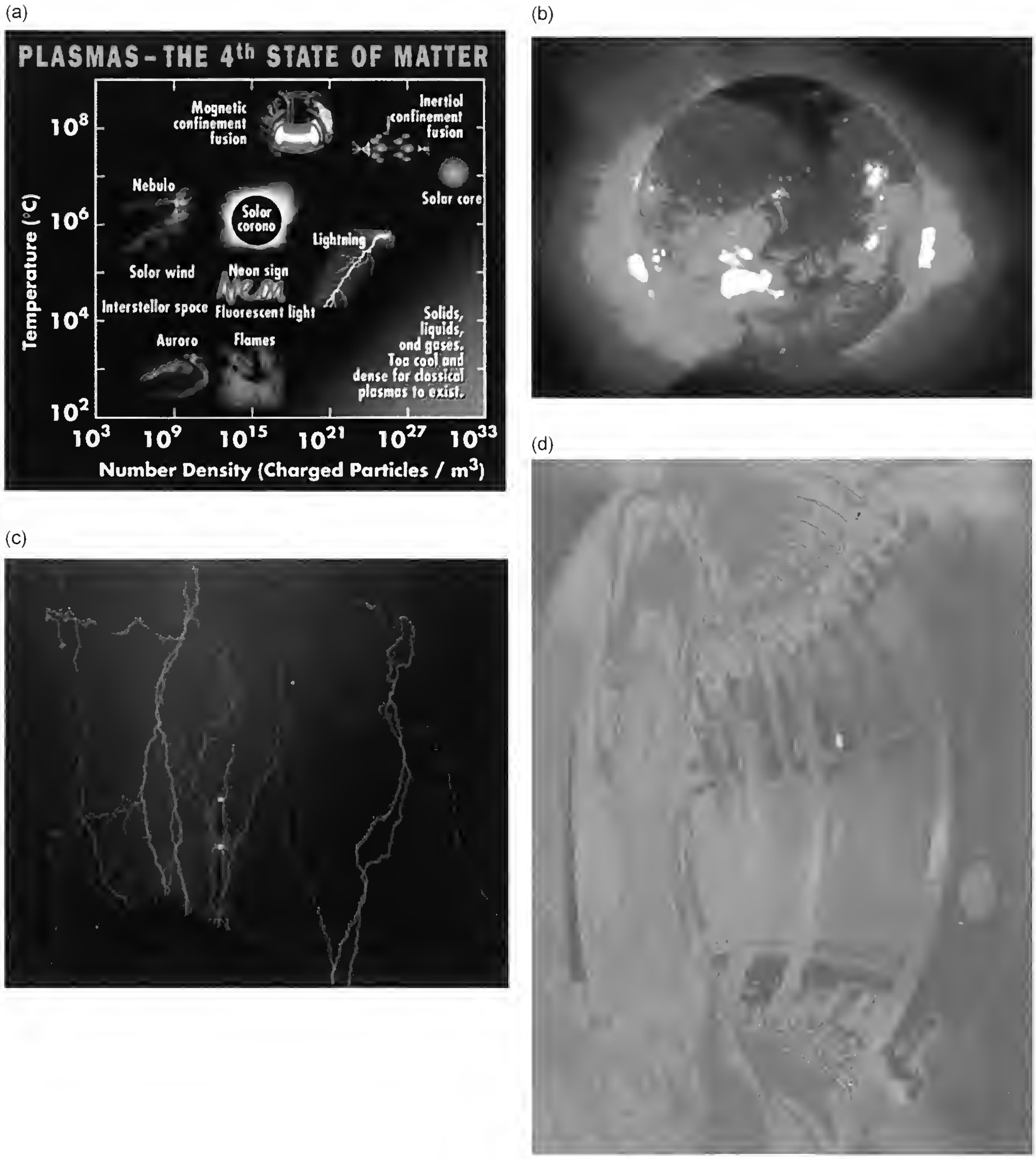

Figure 1 (a) This shows different plasmas in terms of their temperature in K, and the number density (no. of charged particles/m^3). The range of temperatures spans more than six orders of magnitude, while the number density spans more than 30 orders of magnitude. <http://fusedweb.pppl.gov/cpep/chart_pages/5.plasma4statematter.html>. (b) The sun—a functioning fusion reactor. (c) Lightning, a dramatic natural, terrestrial, plasma occurrence. (d) The interior of the JET tokamak. The infrared camera reveals the heat loads on the wall and sometimes the radiation from the very cold areas of the plasma. The experiments in JET done with the brand new ITER-Like -Wall (the JET wall has been constructed to resemble the ITER one in its material aspects) help to develop the best experimental routine for ITER. JET's successor ITER aims to demonstrate that it is possible to produce commercial energy from fusion. EFDA - JET <http://www.efda.org/2011/09/iter-like-wall/?view=gallery-265>.

interplanetary medium]. Near the Earth we have natural plasmas [the polar aurorae, the Van Allen belts, the ionosphere and lightning (Figure 1c)]. Only here on Earth plasma is not a normal state and has to be produced [flames, neon signs, fluorescent lights, rocket exhausts, plasma displays (e.g. TV), electrical discharges (arc lamps, arc welders, plasma torches, sparks), and fusion-energy experiments].

Plasma is characterised by its temperature [related to the energy of its constituent particles, so it is sometimes measured in energy units (eV) rather than temperature (K): 1 eV is about 1.1×10^4 K], and by the number density (charged particles/m^3) of its constituent particles. From Figure 1a, it can be seen that both temperature and density span many orders of magnitude for plasmas.

Clearly, because of the great abundance of plasma in the universe, an understanding of its behaviour, i.e. plasma physics, is of fundamental importance.

PLASMA DESCRIPTION

There are two main descriptions of plasma.

(1) Macroscopic (large scale) – this treats the constituents of a plasma (ions and electrons) as fluids, with average properties e.g. density, temperature and mass velocity. In a fully ionised plasma there may be only one species of ion, and electrons, but in more complicated cases there may be several species of ions, and even un-ionised atoms, as well as the electrons. This is the plasma-fluid model, sometimes known as the continuum or magnetohydrodynamic (MHD) model.

(2) Microscopic (small scale) – where the velocity distributions of the different types of particles are used to describe the medium at each space and time location. This is clearly a more detailed view than in (1) but does not follow the individual identity of every single constituent particle. This is the plasma-kinetic model. It should be noted that a useful fluid model can be derived from the microscopic one under certain conditions, and that the so-called transport coefficients of the fluid model (e.g. viscosity, thermal conductivity) can be calculated from the microscopic model.

An alternative approach is to use the enormous computing power at present available and to follow the motion of individual charged particles making up the plasma. However, even with present computer performance, the number of particles able to be treated in this way is limited.

There is a parallel here with the description of a neutral gas. In order to describe such a gas in macroscopic (fluid) terms, the mean free path for collisions (the average distance travelled by the particles making up the gas between collisions) must be smaller than all other lengths of interest. In the opposite limit of very large mean free path, the motion of individual particles can be considered. The intermediate regime is treated by considering the velocity distribution functions of particles. For plasma the situation is more complex, because there are more lengths of interest: (i) the Debye length which is a radial measure of the sphere of influence of a positively charge particle in the plasma (for a plasma this length must be small compared with other lengths of interest and there must be many particles inside the so-called Debye sphere); and (ii) when there is a magnetic field present (as there often is) the radii of gyration of the electrically-positive ions and negative electrons in the magnetic field.

The model to be used to describe a plasma depends on the problem under consideration.

PLASMA PHYSICS STUDIES

Plasma physics is required for many different areas: (i) astrophysics, dealing with subjects such as the core of the sun and the transport of energy from it to the solar corona, the solar wind (which is a continuous stream of particles impinging on the earth's magnetosphere), the Van Allen belts which are made up of charged particles trapped in the earth's magnetic field), and space exploration by means of rockets with ion thrusters; (ii) closer to earth, plasma physics is required for lightning studies, and communications (e.g. the propagation of electromagnetic waves in the ionosphere); and (iii) on earth, plasma physics is required for studies of MHD energy conversion, solid-state plasmas, low-temperature plasmas and plasma chemistry, and atomic physics. As indicated above, one of the main areas of plasma physics has been the study of plasmas relevant to fusion-energy production.

FUSION-ENERGY PRODUCTION

This section covers some of the material given in a talk delivered to the Royal Society of Western Australia on 15 October 2012 (Green 2012). One of the significant areas of plasma study has been that of thermonuclear plasmas, where 'thermonuclear' means that significant fusion reactions may take place by virtue of the high temperature of the fuel. In other words, the energy of the fuel particles (say the nuclei of deuterium, an isotope of hydrogen) is sufficient to overcome the electrical repulsion between the positively charged nuclei (see equation 1). The temperatures for this to occur are very high (of the order of 100 million K), and matter at this temperature is in the plasma state.

There are many possible fusion reactions (Table 1) but the one most easily accessible (i.e. requiring the lowest temperature for significant fusion reactions to occur in the plasma fuel) is that involving a fuel made up of the isotopes of hydrogen; deuterium (D) and tritium (T). Deuterium exists naturally, and 1 part in about every 7000 atoms of hydrogen is deuterium, so there is an enormous abundance of it, and it is easy to extract from seawater. However, tritium is non-naturally occurring and has to be generated. This can be done by allowing the neutrons produced in DT fusion reactions to interact with the isotopes of lithium (Li) (see equation 2). In these equations energy is required for the reaction with Li6 to proceed, whereas energy is produced in the reaction with Li7.

$$
\begin{aligned}
&{}_0n^1 + {}_3Li^6 \rightarrow {}_0n^1 + {}_1T^3 + {}_2He^4 - 2.5\ \text{MeV} \\
&{}_0n^1 + {}_3Li^7 \rightarrow {}_0n^1 + {}_1T^3 + {}_2He^4 + 4.8\ \text{MeV} \qquad (2)
\end{aligned}
$$

Lithium occurs naturally, is abundant and easily mined or extracted from seawater. This means that fusion

Table 1 Some of the many possible fusion reactions.

	Reactant 1	Reactant 2	Product 1	Energy of 1 (in MeV)	Product 2	Energy of 2 (in Mev)
1a	${}_1D^2$	${}_1D^2$	${}_2He^3$	0.82	${}_0n^1$	2.45
1b	${}_1D^2$	${}_1D^2$	${}_1T^3$	1.00	${}_0n^1$	3.03
2	${}_1D^2$	${}_1T^3$	${}_2He^4$	3.52	${}_0n^1$	14.08
3	${}_1D^2$	${}_2He^3$	${}_1p^1$	14.7	${}^2He^4$	3.7

Chemical symbols: D, deuterium; T, tritium; p, proton; n, neutron; He, helium.
Subscript is the atomic number i.e. the number of protons in the nucleus e.g. 2 for He.
Superscript is the number of protons and neutrons in the nucleus e.g. He has 2 protons in the nucleus and there are 2 isotopes; ${}_2He^3$ with one neutron in the nucleus, and ${}_2He^4$ with two neutrons in the nucleus.
Unit of energy, MeV, is approximately 1.6×10^{-13} J. While each reaction produces an apparently small amount of energy, there are a large number of such reactions (of the order of 10^{23}) in each mole (molecular mass in grams) of the reacting material.
1 g mass of D undergoing reactions 1a +1b (each with 50% probability) releases about 25 000 kWh/g mass of the reacting nuclei: cf. hydrogen and oxygen which release 4.4×10^{-3} kWh/g mass of the reactants.

fuel is readily available for millions of years, and indeed, if DD fusion could be achieved, there is no necessity for lithium fuel, and the source of energy is essentially unlimited.

However, to achieve the conditions necessary to produce and extract fusion power for useful purposes (electricity production, high-temperature heat for industrial processing, desalination, or the production of hydrogen for use as a clean fuel in fuel cells) is a huge challenge. It is a most seductive challenge, because its solution appears to promise an unlimited source or energy, with significant positive environmental features.

Since the late 1950s, many schemes have been studied to extract fusion power from a plasma of hydrogen isotopes, but the main two approaches at present are: (i) magnetic confinement; and (ii) inertial confinement.

Approach (i) uses a magnetic 'bottle' (mainly formed by electric currents in coils outside the reactor, but sometimes supplemented by magnetic fields arising from plasma currents) to confine the plasma, while it is heated and the fusion energy extracted, in a steady-state manner.

Approach (ii) uses energy-dense beams (e.g. lasers, ion beams) to irradiate targets made of fusion reactant materials (e.g. deuterium and tritium). This irradiation causes the target to be heated and the constituent matter to fuse in a 'pulsed' manner. The confinement (the state in which the reacting plasma stays together) is determined by the inertia of the fuel.

The plasma temperatures required for a reactor plasma have been achieved, and significant fusion power has been produced (16 MW peak), but the production of more energy than is required to establish the fusion plasma, and the maintenance of reactor conditions for times of reactor interest, remain to be established.

The magnetic confinement scheme which is, at present, closest to achieving reactor-like plasma conditions is the so-called tokamak. This is a scheme, first developed in the Soviet Union, and the word 'tokamak' is a Russian anagram for toroidal magnetic chamber. One of its main features is that it requires a significant current flowing in the plasma to establish its confining magnetic field. However, another scheme called the stellarator has potential advantages (in that it does not require a significant plasma current to flow), and research in this area continues and provides support for the tokamak studies.

The international project ITER (www.iter.org), which involves a tokamak, is at present being constructed in the south of France, and aims to provide information necessary for the construction of a prototype/ demonstration fusion reactor.

The development of special plasma measurement systems (so-called plasma diagnostics) has been necessary to understand plasma behaviour. For example the measurement of the properties of these extremely high-temperature plasmas in fusion energy studies presents a challenge because no material probe can survive being placed in such a plasma. One active measurement of electron temperature uses an intense laser beam, which is fired into the plasma. This highly monochromatic light is scattered by electrons in the plasma. and the scattered light is collected and measured. The absolute scattered signal strength depends on the number of scattering centres (electrons) per unit volume i.e. the plasma density, and the broadening of the incident laser light is the result of the Doppler effect (electron motion affecting the frequency/wavelength of the laser light in the scattering process). Thus the mean velocity (energy) of the electrons in the scattering volume can be determined, and this is essentially the electron temperature.

JET is the world's largest tokamak at present and has achieved conditions closest to those required in a fusion reactor. Figure 1d shows the interior of the JET device and how infra-red diagnostics can be used to understand the impact of the hot plasma on the material walls of the material container. Of course, the confining magnetic field is arranged to reduce this impact so that it is tolerable.

SCIENTIFIC AND TECHNOLOGICAL APPLICATIONS

There are many ways in which plasma-physics knowledge has been applied. Some are: plasma

processing (plasma-based materials processing technology which aims to modify the chemical and physical properties of surfaces e.g. spraying, and etching in microelectronics); improved lighting (fluorescent lights); the production of ion beams (e.g. for ion implantation to change material bulk properties as in semiconductor device fabrication); plasma processing of waste; metal cutting and welding; the new therapeutic techniques of plasma medicine; plasma acceleration (to improve on conventional particle accelerators); non-thermal plasmas used in food processing; MHD generators for directly generating electricity from the thermal and kinetic energy of plasma; and solid state plasma (electron-hole plasmas, atomic physics) and plasma chemistry.

Knowledge gained in the study of plasma physics has wide application in other scientific and technological areas. One major example involves the computational modelling of plasma. Fluid codes, which attempt to model the many fluids making up a plasma (e.g. different species of ions and electrons) have been used in studying the propagation of fire. Such fluid codes already existed in fluid studies (e.g. weather and climate codes) but dealing with the complexities of plasma description has led to advances in numerical computation techniques.

For fusion research, many different technologies are required, and the development of them has had applications in other fields. Some of the technologies involved are: ultra-high vacuum; remote handling; computerised control and data acquisition (one development led to the control of in-line strip production of stainless steel); pulsed power supplies and switching; instrumentation and measurement systems (in particular laser systems); electromagnets; thermal shielding and cryogenics; and the development of high heat-flux resisting materials (applications in brakes and clutches in aviation, trains and motor racing, and actively-cooled components for space vehicles). Perhaps one of the largest spin-offs (or technology transfers) comes from the requirement of producing high-magnetic fields and maintaining them for long periods of time (a requirement also shared by particle accelerators). This has led to the development of advanced superconducting strands which are now used in the magnets of magnetic resonance imagers (MRIs) in hospitals all over the world to carry out body scans (Figure 2).

Knowledge transfers occurs through researchers who move to other areas bringing with them the skills they have developed in plasma-physics research. This kind of cross-fertilisation and inter-disciplinary studies are important forces driving scientific and technological progress.

BRIEF REVIEW OF AUSTRALIAN INVOLVEMENT

An Australian, M Oliphant, was one of the 'fathers of fusion' (see above) in the early 1930s. P Thonemann (Australia) and G Thomson (UK) pioneered, in the mid to late 1940s, magnetic-confinement research in the UK. M Oliphant returned to Australia in 1950 and commenced plasma-physics research at the Research School of Physical Sciences and Engineering at the Australian National University (ANU) in 1958. This work continues to this day and now involves a national experimental stellarator facility as well as theoretical studies. C Watson-Munro established (1961) a department of plasma physics in the School of Physics at the University of Sydney, and this work also continues. In the 1960s B S Liley built and operated the first tokamaks outside the Soviet Union at ANU. This work continued into the 1970s and 1980s but the experimental work was subsequently altered to that involving a novel stellarator.

Flinders University became involved in magnetic confinement studies, the University of New South Wales carried out an inertial confinement research program, theoretical work was carried on at the University of

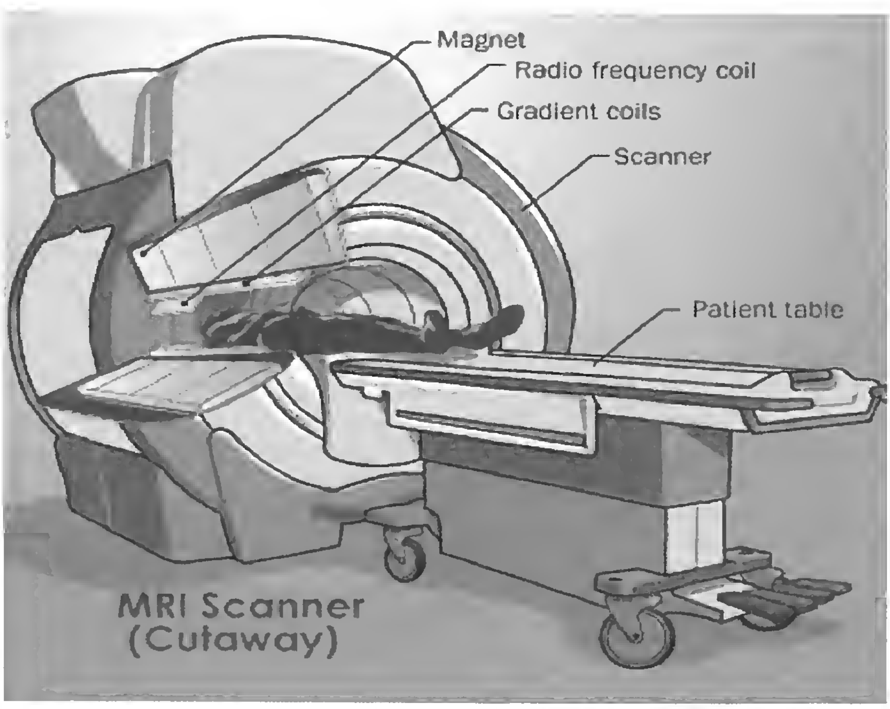

Figure 2 Magnetic Resonance Imager showing the (super-conducting) magnet <http://www.magnet.fsu.edu/education/tutorials/magnetacademy/mri/>.

Melbourne, and by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The Australian Nuclear Science and Technology Organisation (ANSTO) has also been involved in fusion-related studies, in particular in the study of materials required to withstand the hostile environment of a fusion reactor interior. Such materials studies are also being carried out elsewhere, e.g. at the University of Newcastle. Fundamental studies on plasma processes are being carried out at the Curtin University.

This brief summary does not properly describe all the individual contributions made by the different Australian research groups, but one thing is clear, plasma research in Australia has produced a significant number of scientists who have participated/are participating in the international research and development program involving plasma studies, many of them in the fusion program.

At present, Australian fusion researchers are looking for the opportunity to participate in the ITER Project and subsequent fusion-reactor development. They have established an interest group, the Australian ITER Forum, and have prepared a document 'Powering Ahead: A National Response to the Rise of the International Fusion Power program' (http://fusion.ainse.edu.au/iter/australian_fusion_strategy2). This document will hopefully persuade the Australian Government to negotiate with the partners of the ITER organization to allow Australians researchers to participate.

CONCLUSIONS

1. Plasma is the most common form of visible matter in the universe and as such, the study of plasma physics is fundamental to an understanding of the universe.

2. Not only is plasma physics of basic interest, but there are also also many applications which have been developed based on our understanding of plasma behaviour.

3. The study of plasma physics has many possible applications in other areas of research and development.

4. The realisation of fusion energy from plasma fuel could solve the world's energy crisis in that it could provide an environmentally-friendly source of energy, with essentially a limitless supply of fuel.

5. Australian researchers are looking for support to continue their fusion studies as part of the international program. Without appropriate government support, this area of research will not be sustainable in Australia.

ACKNOWLEDGEMENTS

I thank Journal reviewers Ron Burman and Brian James for their helpful comments.

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Received 19 December 2012; accepted 22 March 2013

Geomorphology of pit gnammas in southwestern Australia

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Most granite rock outcrops in the Wheatbelt and Goldfields have numerous shallow pan gnammas generally on the flattish upper parts of the dome, but some rocks have single or a few deep pit gnammas often on the lower flanks. The classic pit gnamma is subcircular in plan, hemispherical in profile and formed by weathering of homogeneous granite. This and minor variations account for about 60% of the 80 pit gnammas studied in the Wheatbelt and Goldfields. Previous studies suggest depth is greater than width or about half of width in pit gnammas, but 76% of the study gnammas had a D:W ratio between 0.2 and 1.0, still much greater than in pan gnammas.Because of the influence of preferential weathering along joints, and because some have been formed by running water, some pit gnammas are of unusual shape and profile, so that 10 types are recognised: hemispherical (two varieties), cylindrical, canoe, trough, underground shelf, flask, lotic potholes and plunge pool (two varieties). Most have a distinctive plan and profile and some have characteristic locations on a rock or distinctive morphometrics. Two further types of pit gnammas, armchair hollows and pipe gnammas, are known in Australia but not in the study area.

KEYWORDS: canoe gnammas, eversion, granite outcrops, joints, pan gnammas, pit gammas, rock basins, weathering

INTRODUCTION

Gnammas, or rock holes, occur commonly on granite outcrops in the southwest of Western Australia (Pinder *et al.* 2000). They are of two basic types: pan gnammas are of diverse shape in plan, shallow, flat-floored and seasonally filled with water while pit gnammas are typically subcircular in plan, have a depth to diameter ratio exceeding 0.2, and contain water for longer periods (Twidale & Vidal Romani 2005; this study). Pan gnammas are far more common than pit gnammas but it is the pits that are of human interest because of their value as water sources in a dry and inhospitable countryside (Bayly 2011). These days, local councils and tourist authorities in South and Western Australia have marked the presence of some with signage so that the public is aware of them and their significance, more so than for pan gnammas. Unfortunately, to protect the public from their own folly, many larger ones have been filled in or covered (e.g. at War Rock, via Morewa and the Moningarin Gnammas via Cadoux), so reducing opportunities for study.

Indigenous Australians have long been familiar with these natural water-storage pits in Australia's desert regions where they were vital to their survival (Bayly 1999). The Nyungar people used the anglicised 'gnamma' to describe the rock hole and its retained water, if any (Bayly 2002a, 2011). Hence the term 'gnamma hole' is a tautology and though widely used, is incorrect. The first scientific references to them were by Ormerod (1859) on granitic rock holes in England and Hartt (1870) on similar holes in Brazil. In Australia, early miners in the Goldfields soon realised their value and perhaps the earliest record of this is Göczel's diagram of a pit gnamma in the first annual report of the Western Australian Department of Mines (Göczel 1894). Thereafter there were many skirmishes between local Aborigines and the new explorers, miners and pastorialists over the water in the gnammas (Bayly 2002a,b, 2011; Carnegie 1898). The location of gnammas often determined the route of early European tracks (e.g. the Holland track to Coolgardie: Underwood & Elliott 2002) and sometimes the location of early homesteads (e.g. the Wattoning Homestead north of the present day Mukinbudin: Anon 2013). An early scientific paper on gnammas by Maclaren (1912) explained their origin by initial flaking due to insolation thus forming a hollow, and then weathering of the granite by the collected water, and the importance of hardening of the orifice by mineralisation and hence slowing of its widening. Other early publications to mention gnammas in Western Australia include Woodward (1912, 1916), Talbot (1912) and Jutson (1934).

The word 'gnamma' is now widely used by scientists, both locally (Twidale 1971) and also overseas (Domínguez-Villar & Jennings 2008), applying it to depressions in rock both of the pan and pit types, usually in granite. It is the pits that have a utilitarian value (Bayly 2011) so most lay people think of deeper rock hollows when the word gnamma is mentioned. The mode of origin of pit gnammas intrigued many authors. A very early explanation in England proposed that rock hollows were the work of Druids and in Australia indigenous people often claim ancestral beings dug them out in the 'dreamtime.' An example is the row of five pit gnammas 14 km north of Trayning; according to signage at the site they are attributed to Nyimgarn, the echnida, digging pits as he migrated south from Ninghan Station and Lake Moore.

Gnamma formation is a three-stage process: initiation of a depression, breakup of the rock, and finally evacuation of the debris. Apparently initial depressions have many causes ranging from insolation causing flaking, to breakdown of crystalline irregularies, to lichen attack and to subaerial weathering by attack of acid groundwater on bedrock granite (Twidale & Corbin

1963). Proposals for mechanisms of rock breakup include the continual role of insolation and attack of xenoliths, the direct action of wind and running water, and glacial ice. Majority opinion (Twidale & Corbin 1968; Twidale & Romani Vidal 2005) supports the weathering of bedrock granite by alternate wetting and drying. Excavation of weathered material is by wind or in solution or by human interference (Twidale & Romani Vidal 2005). These processes form a basic shape of a roundish, hemispherical basin, supposedly deeper than wide. Magnification of weathering along joints leads to the formation of elongated 'canoe'-type gnammas (Twidale & Corbin 1963). Observations incidental to the study of the biology of 80 gnammas in southwestern Western Australia (B V Timms in prep.) suggests that many local gnammas do not fit these descriptions and may have originated by geomorphic processes that differ from those described in the literature.

The aim of the present study is to describe the geomorphology of these 80 pit gnammas and prepare a classification of them. Particular attention is given to structural parameters and possible modes of origin.

METHODS

Pit gnammas are uncommon compared with pan gnammas. They occur singly or in very small numbers on just a small proportion of the numerous granite outcrops across southwestern Western Australia. While quite a number were easily located via roadside signage (e.g. the five gnammas 14 km north of Trayning), the locations of many were brought to the attention of the author by local enthusiasts at Beacon, Mukinbudin, Hyden and Norseman, and by colleagues. Thus those in the study tend to be clumped around those townships (Figure 1; Appendix 1).

Most gnammas were visited four to five times in 2010–2012, associated with limnological studies (B V Timms in prep.), so many were seen full, in various stages of filling, and also when dry. Length, width at right angles to the length, and depth were measured with varying degrees of accuracy: depth to the nearest centimetre, and length and width varying between centimetre for small gnammas with distinct rims, to 50 cm for large round gnammas with sloping edges (e.g. Beringbooding North with a recorded diameter of 12 m, the estimation confounded by lack of a rim and no observation of its water line when overflowing). In most cases the depth measured was of necessity to the surface of bottom sediment, and hence the measurement is not the true depth of the rock hole. The few exceptions were those gnammas freshly cleaned of their soft infill (indicated in Appendix 1). Lengths and widths were also often difficult to determine exactly, especially where the edge was sloping; a good guide was the full water level, but taking care not to include situations where there was shallow flooding of the surrounding rock. For elongated gnammas width was measured at a few places to get an average value which was important in volume calculations. Another inaccuracy occurred when the rim overhung underlying cavities. Such cavities were most developed in gnammas on a major vertical joint so that the joint was perhaps excavated in some cases up to 50 cm below the rim; this is not recorded in the measurements in Appendix 1. Another even greater measurement problem was presented in those gnammas where a deep horizontal joint had been hollowed underground (Wattoning and Horse Collar Gnammas: Appendix 1): it was impossible to measure these underground dimensions, so that the values recorded are of the visible cavity.

Volumes for most gnammas were calculated assuming the basin shape was a 3D parabola and using the formula

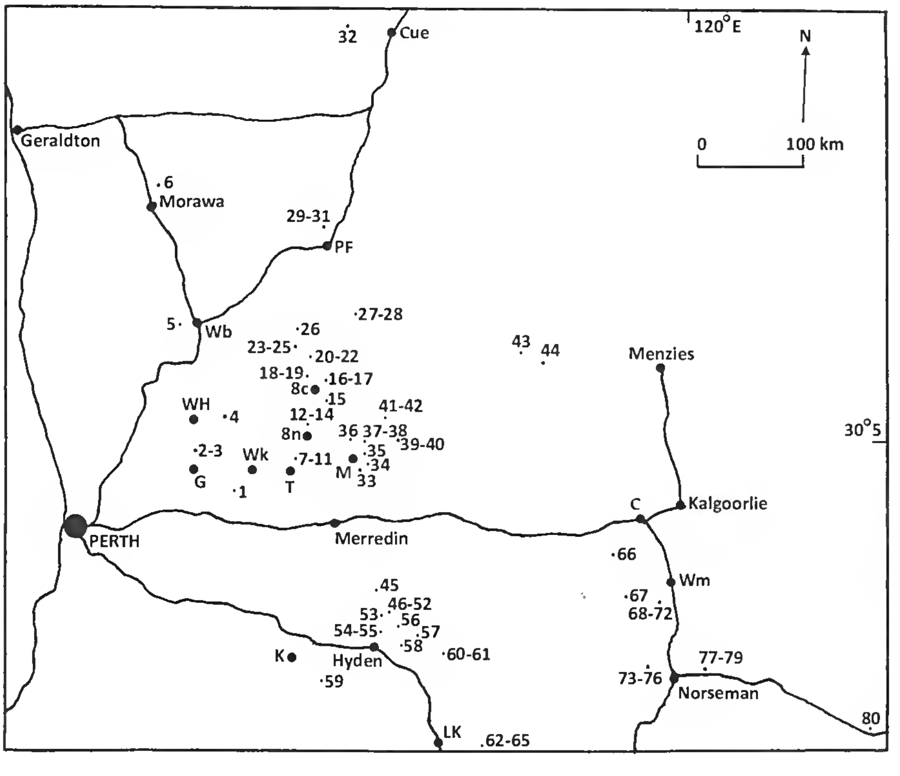


Figure 1 Map of the study area in the Wheatbelt and adjacent Goldfields showing the location of the 80 pit gnammas as listed in Appendix 1, associated major roads and towns. C, Coolgardie; Bc, Beacon; Bn, Bencubbin; G, Goomalling; K, Kulin; LK, Lake King; M, Mukinbudin; PF, Paynes Find; T, Trayning; Wb, Wubin; WH, Wongan Hills; Wk, Wyalkatchem; Wm, Widgiemooltha.

$V = d^2h\pi/8$ where V is volume, d is mean diameter and h is depth. For those with a near-rectangular shape or triangular profile (most type 3 and 4 gnammas, see Appendix 1) the formulae $V = lwh$ was used where l is length, w is width, h is height for near-rectangular gnammas, with $V=lwh/2$ for triangular gnammas.

The position of each gnamma on a granite outcrop was noted, particularly whether on the flattish top, the slide slopes or on the lower flattish flanks. Each gnamma was photographed, including when dry in most cases, thus providing images when later analysing shapes and possible origins (Figure 2).

RESULTS

The gnammas varied in mean diameter from 0.19 to 12 m and in depth from 24 to 300 cm (Appendix 1). The majority of gnammas were 1.0–2.5 m in mean diameter (Figure 3a) and 50–100 cm deep (Figure 3b). The 12 m-diameter gnamma on Beringbooding Rock, and the 3.8 m-deep gnamma at Cadigan are exceptional, though there is an even larger gnammas on Jindarra Rock North of Elachbutting Rock (W Bayly pers. comm. 2010) and on King Rock via Hyden (Twidale & Vidal Romani 2005). True depths are probably greater than indicated as many gnammas had more than a few centimetres of sediment at the bottom. As indicated in Appendix 1, some were cleaned out during the study, so it is only for most of these that the true depth is known (though the Bullamanya pits were impossible to clean out completely without mechanical assistance). The depth:width ratio was 0.57 (95% confidence limits via Fieller's Theorem 0.26 – 0.88) a figure which would be somewhat higher if the true depth of each hollow was known, but still not greater than 1 in most cases.

While most gnammas are of the hemispherical to parabolic pit shape, not all are circular in plan and with smooth and even rims (Figures 2, 5). Many have rims interrupted by minor joints and laminations up to 10 cm deep around the rim and bending with it and extending to some depth within the hollow. Some of these laminations are incomplete, mainly above the usual water line. An example is Quanta Cutting Gnamma. In some the sides are vertical (e.g. Cadigan Mid and South Gnammas), in many the sides tend to be steep (60–80°), but in others side slopes are moderate at 20-30° (e.g. the Willogyne Gnammas). The sides may be smooth, but minutely rough revealing individual grains in the rock, or rough at a greater scale of many centimetres because they are interrupted by joints and attendant missing or protruding blocks.

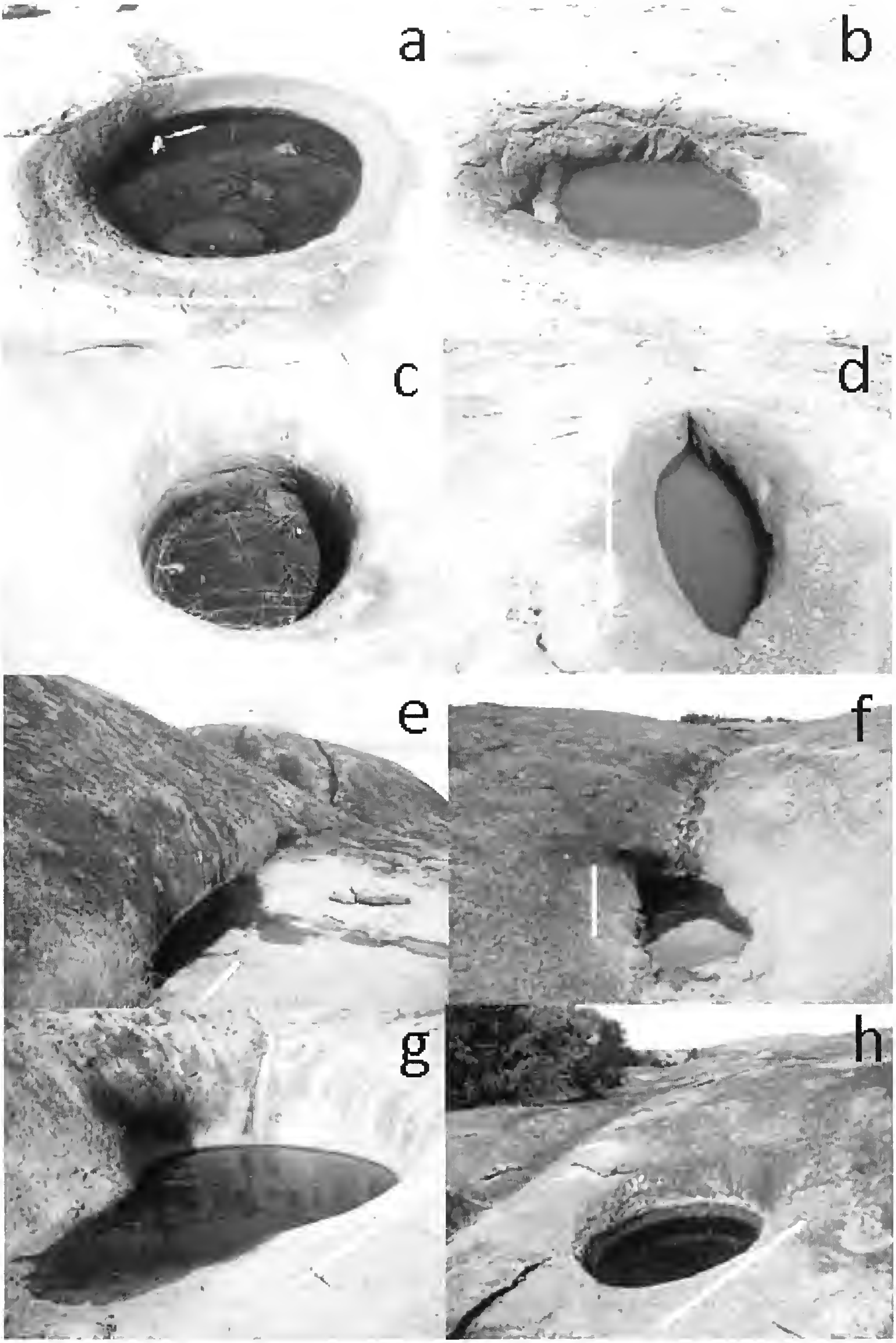
Quite a few gnammas lie on major vertical joints. These usually influence their shape, so that they are elongated along the joint but often narrowing at each end to give an overall 'canoe' shape in plan. Many of these are undercut along the joint, at least at one end. Also, most tend to have vertical sides (e.g. Trayning Far Northwest Gnamma: Figure 2d), though those of Twine Scrub Gnamma has steep parabolic sides, and the Granite Creek Gnamma has a hemispherical cross-section. A few gnammas are also elongated along a major joint, but the joint has not been enlarged, so that the cross-section is triangular (e.g. Higgensville North Gnamma) or in the cases of the War Gnamma and Balladonia Gnamma vertical on one side (Figure 2e).

Rarely a pit gnamma is wider underneath than on the surface. This can occur in homogeneous rock, in which the only known case in the present study is the small flask shaped gnamma on Lillian Stokes Rock (Stokes Far South Gnamma). In two cases the underground expansion is along a horizontal joint 24 cm (Horse Collar Gnamma) to 100 cm (Wattoning Gnamma) from the surface. In both cases the horizontal extent of the cavity is unknown, but at least 50 cm on one side of Wattoning Gnamma and probably much bigger in the case of Horse Collar, as it was known in the early days to water stock without drying, despite its visible small volume (R Trenorden pers. comm. 2010)

All of the above pit gnammas occur on flattish rock surfaces either at the base of elevated exposures of granite or on sheets of granite exposed at ground level, and significantly are not associated with waterways. However there are two groups of gnammas on waterways, which often occur on the steeper slopes of granite exposures. The first group lie on larger waterways often utilising a major joint that has been eroded a little. Examples on Isoetes, Roe and Cave Rocks are elongated, steep sided and in profile are deep upstream and shallow downstream. The Twine Far North pit gnamma is somewhat different as it is at the base of the rock outcrop and on a joint scarcely enlarged though it is deeper upstream. The second group superficially resemble the common roundish pit gnammas with steep sides, but they lie on waterways at the bottom of a steep slope. Like the first group some are deeper rearwards and have shallower overflow lips (both Bullamanya North and South Gnammas, and Yanneymooning Gnamma: Figure 2h), but two are steep-sided round holes with even floors (Twine North and Bullamanya Upper North). Four are on watercourses active after rain, but the waterway has changed course at Yanneymooning and now does not flow through the gnamma.

DISCUSSION

Pits due to the physical and/or chemical weathering on exposed rock surfaces are common in many parts of the world and in many types of rocks (Twidale & Corbin 1963; Twidale & Vidal Romani 2005). Numerous terms are used to describe them, some of local validity and restricted to particular types and others such 'weathering pits' more universal and descriptive. The most common rocks attacked are sandstones (Netoff *et al.* 1995; Chan *et al.* 2005) and granites (Twidale 1971; Domínguez-Villar *et al.* 2009). Studies often classify subtypes based on their physical shape and on the processes forming them. For instance Netoff *et al.* (1995) recognised shallow pans, deeper bowls and cylinders, and armchairs in sandstone in southeastern Utah. Weathering hollows in granites are often called gnammas (see above) and the shallow pan types have been studied in Western Australia (Pinder *et al.* 2000; Timms 2012a, b and references therein), Chile (Domínguez-Villar 2006), Portugal (Domínguez-Villar *et al.* 2009), Spain (Vidal Romani 1983) and USA (Domínguez-Villar & Jennings 2008) among other places. The deeper pit gnammas are less common and litttle studied.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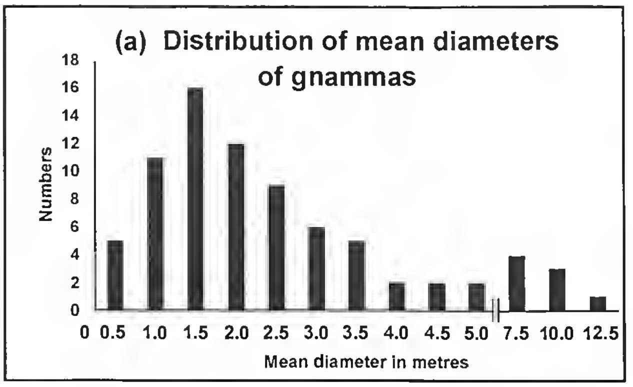

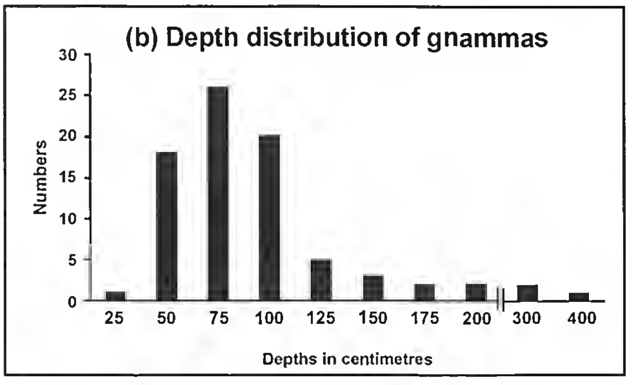

Figure 3 (a) Frequency distribution of mean diameters of the 80 pit gnammas; note most size intervals in 0.5 m steps, but last three in 2.5 m steps. (b) Frequency distribution of the depths of the 80 pit gnammas; note most depth intervals in 25 cm steps, but last two in 1.0 m steps.

A pit gnamma is defined by Twidale & Cobbin (1963) as a rock hollow elliptical or circular in plan and semicircular in cross-section with a large depth relative to the maximum diameter. In contrast, pan gnammas have flat floors and a small depth:diameter ratio. This ratio has only been partly quantified, with a value of D:W >1 suggested for pits by Twidale & Corbin (1963) and a ratio of ~0.5 by Twidale & Vidal Romani (2005). It is not clear if the diameter these authors used was the maximum or mean, though probably not the minimum. Morphometrics of the present set of pit gnammas suggest that if the mean diameter is used, 12.5% qualify by the first ratio and 36.25% by the second ratio. Twidale & Corbin's ratio was apparently based on two pit gnammas on Pildappa Rock South Australia, but these have actual ratios of 0.27 and 0.20 (B V Timms unpubl. data), so that perceptions by eye are tricked. Their ratio is obviously too restrictive, and even that given by Twidale & Vidal Romani (2005) is not very helpful. From the present study, 44% of gnammas have a ratio between 0.2 and 0.4, and 76% a ratio between 0.2 and 1.0 (Figure 4), with a mean of 0.57. A ratio of D:W >0.2 fits the data much better and still distinguishes pits from pans, in that pan gnammas have ratios <0.1 [Dominguez-Villar et al. 2009; 0.026 for 100 pan gnammas on 10 rocks in the Western Australian Wheatbelt (B V Timms unpubl. data)]. Even this lower value of 0.2 excludes 12.5% of present gnammas, though most of these would qualify if the true rock basin depth was available and used. At the other end of the scale five gnammas have values >2 (Figure 4); all have small diameters and deep cylindrical pits thus distinguishing them from other pit gnammas (see below).

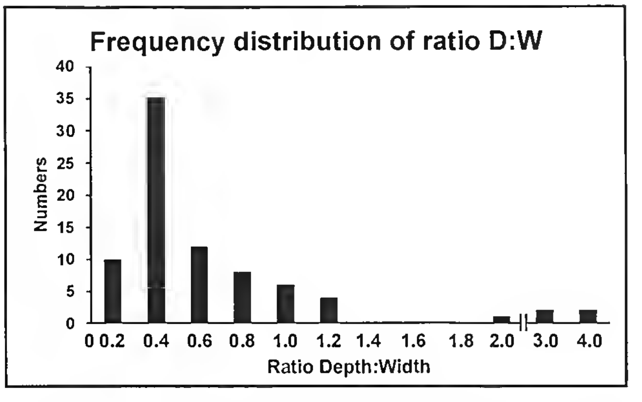

Figure 4 Frequency distribution of depth:width ratios; note most intervals in 0.2 steps, but last two in 1.0 steps.

Table 1 Types of pit gnammas and their frequency percentage.

Type	Name	Description	Percentage
1a	Hemispherical	Hemispherically shaped, no microlayering or joint control	21.25
1b	Hemispherical	Hemispherically shaped, with layering and/or minor joint influence	30.00
2	Cylindrical	Cylindrical due to dominant vertical solution	11.25
3	Canoe	Elongated 'canoe' shape, due to major joint control	17.50
4	Trough	Sitting along a major joint between two rock blocks	5.00
5a	Underground shelf	Expanded depthwise at a lower horizontal joint	2.50
5b	Flask	Expanded depthwise in homogenous rock	1.25
6	Lotic potholes	Eversion trench along a waterway	5.00
7a	Plunge pool	Plunge pool on a water course, presently active	5.00
7b	Plunge pool	Plunge pool on a previous water course, now inactive	1.25

◀ **Figure 2** Representative pit gnammas. (a) Type 1a, Dingo Rock Gnamma; note infilled rocks to prevent human visitors drowning but lizards falling in drown. (b) Type 1b, Oak Flat West Gnamma. (c) Type 2, Cadigan Middle Gnamma. (d) Type 3, Far North West Gnamma of the Trayning Group. (e) Type 4, Trough gnamma on Balladonia Rock. (f) Type 6, Pothole Gnamma on Isoetes Rock. (g) Type 7a, Northern Pit Gnamma on Bullamanya Rock. (h) Type 7b, pit gnamma on Yanneymooning Rock. Scale bars 2 m along length of gnamma.

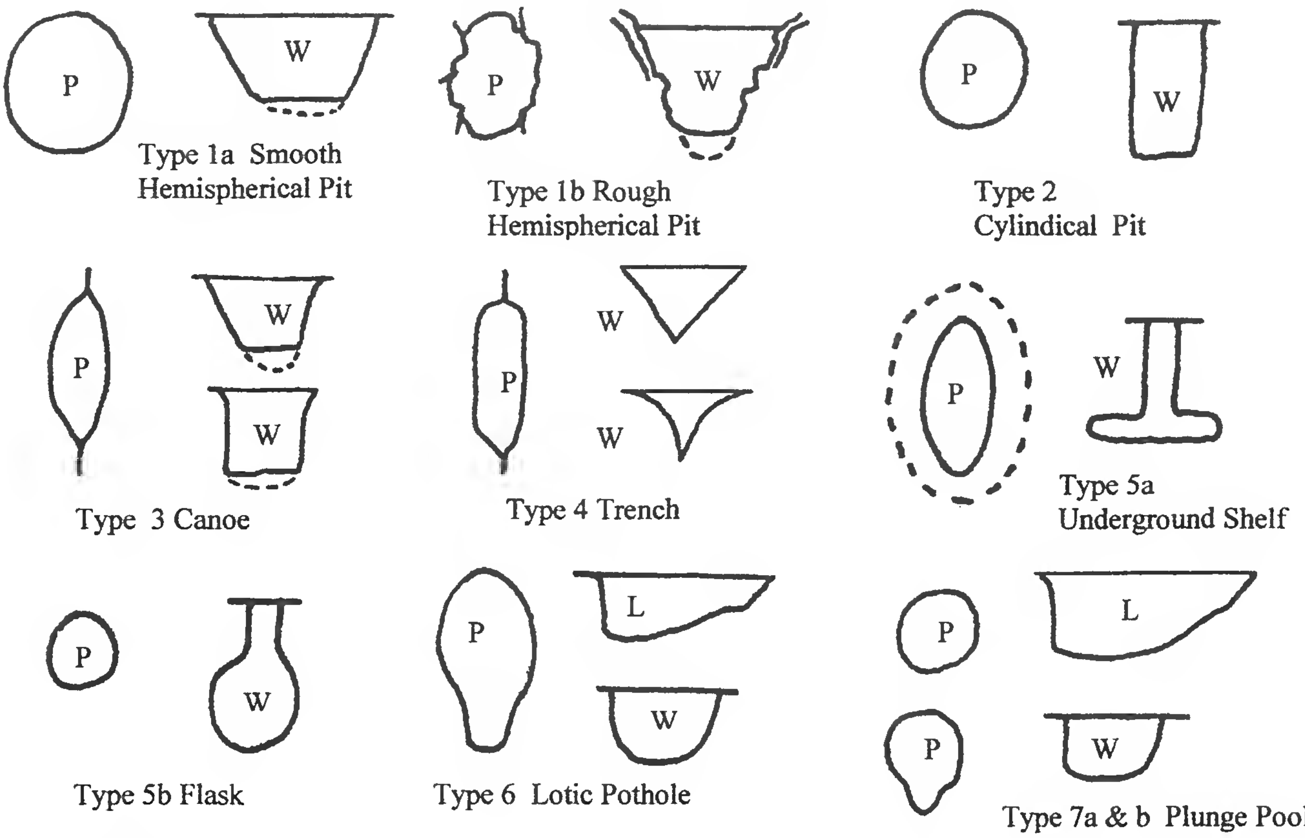

Figure 5 Conceptual profile diagrams of the various types of pit gnammas. L, length; P, plan; W, width; dashed lines are for rock surfaces not seen at ground level.

Many pit gnammas have a hemispherical pit shape and can be accounted for by rock solution subequally horizontally and vertically (Twidale & Corbin 1963; Twidale & Bourne 1976; Twidale & Vidal Romani 2005). This assumes the gnamma fills to about capacity each time it rains and the rock substrate is homogeneous. If there are joints, weathering will be preferential along them, and if the pit collects only a little water in most years it is possible the pit may deepen vertically, though this may be inhibited by accumulated bottom sediment if clayey. However, if sediment is dominated by organics, bottom weathering may be enhanced by contact with carbonic acids. In those pits which have been excavated (Appendix 1) there was no evidence of clay, just organics plus grus. For pits in sandstone, one problem restricting depth is the difficulty in removing weathered sand grains from the base (Netoff *et al.* 1995; D Netoff pers. comm. 2013), although wind is an important eroding factor in shallow pits. It is assumed pits in granite lose most of their rock in solution (Twidale & Corbin 1963) though many have an accumulation of grus and organics on the bottom. This sediment can remain unless indigenous people clean out pit gnammas due to their importance as water reservoirs (D McKellar pers. comm. 1996). With no restriction to natural deepening processes, gnammas on Australian granites have become relatively common, but still sparsely distributed.

Most pit gnammas are modified from the classical profile either horizontally or vertically (see above) and some are due to other processes. The situation is thus more complex than envisioned by Twidale & Corbin (1963) and Twidale & Vidal Romani (2005), with 10 types being recognised in this study (Figures 2, 5; Table 1). The first (Type 1a; Figure 2a) is the hemispherical pit (alias 'pudding-basin-shaped pit') in homogeneous granite due totally to rock weathering by stagnant acid water, as explained by Twidale & Cobbin (1963). It has a hemispheric profile because of equal weathering in all directions. More often than not the horizontal and/or vertical profile is uneven because of minor joints intersecting the basin, these being preferentially attacked by solution; this is Type 1b (Figure 2b), both being recognised by Twidale & Cobbin (1963) though not differentiated in this way. This second group may not be due totally to solution of homogeneous granite, crystal by crystal, but could be assisted by pre-existing abnormalities in crystallisation (e.g. xenoliths in the rock: Twidale 1971) these being more prone to weathering, or in some large gnammas such as Beringbooding North pre-existing sagging in the curvilinear joints of the rock outcrop could define a hollow that is then enlarged by weathering. Many must be exposed to the sun's radiation for long dry periods since there are thin laminations at their rims bending down to depths, such laminations being a feature of the surface of many granite outcrops and generally secondary and due to insolation (Twidale & Vidal Romani 2005). Together these two types account for 51.25% of the present study group (Table 1), which fits the perception of pit gnammas usually being circular and hemispherical in section.

A few pit gnammas (Type 3; Figures 2c, 5) have almost vertical sides all around and are often deeper than wide, with D:W>2 (see above). All are in homogeneous rock: five (Stokes Far North and Far South, Twine

Borehole, Forestiana North and South) are very small, two Karroun pits are bigger, with D:W <1, while the two Cadigan pits are widest and deepest, being in a massive granite layer. All have a small catchment so that perhaps most rarely fill, meaning the little water they do catch weathers the basal rock rather than the shallower rock, which weathers only when the gnamma is full. This would apply to Stokes Far North and Far South, Twine Borehole and the two Karroun pits, all of which were never seen more than half full; others were usually found full or nearly full of water. In the case of the Forestiana pits this is because they now receive overflow water from adjacent pan gnammas, and the Cadigan pits now reach down to a horizontal joint and associated underground springs (R Sache pers. comm. 2011). There is no indication in any of these examples of spiral grooving in the walls due to vortices of water entering forcefully as described by Twidale & Vidal Romani (2005). There is however an unstudied pit gnamma, now usually dry, of this nature on the western side of Victoria Rock; unlike the others it receives considerable volumes of water via overland flow. This cylindrical type is the one illustrated by Göczel (1894), perhaps reflecting that he thought this shape was typical.

It is possible there are more gnammas of Type 3 in the Wheatbelt but they are covered over or filled in, an indication of the danger of steep-sided pits to tourists. One is on Dingo Rock and included in this study, but classified as a hemispherical pit (Type 1a) because the bottom is filled with large rocks and hence not observable in detail. Others covered with a framework and wire mesh occur at Jibebring Rocks, via Wubin, at Moningarin, via Cadoux and at Buldania Rocks via Norseman.

A more common modification of the basic pit gnamma characteristics occurs when they lie on a major joint (Type 3; Figures 2d, 5). Weathering is preferential along the joint so that they are elongated and usually 'canoe' shaped (Twidale & Cobbin 1963). The side walls are narrow, and parabolic or vertical, but rarely a low-angle hemisphere, thus showing the importance of preferential weathering along the joint. Twine Scrub pit has narrow parabolic sides, Trayning Far North pit has wider parabolic sides, Cadigan North pit has vertical sides, and the War pit has the north side vertical and the south side almost a hemisphere. Another feature of these canoe pits is undercutting at one or both ends along the joint. This may extend the length under the rim by 20–50 cm. These canoes are the third most common type (17.5 %; Table 1), and together with above other types account for 82.5% of all pit gnammas.

Four gnammas lie *on* joints between granitic masses, rather than *in* the joints like canoe gnammas, and distinct enough to be considered as Type 4 (Figure 5). Rock weathering has been minimal, so that lateral profiles are triangular or even convex on each side. The Wondoning Hill pit has slightly concave sides, indicating some weathering, the two Higgensville North pits have a triangular profile and the Balladonia pit (Figure 2e) has one side vertical and the other convex. It is possible these are incipient canoe pit gnammas (Type 3), weathering to the usual profile being slower because of infrequent filling.

Three gnammas are expanded underground, two guided by horizontal joints (Type 5a; Figure 5), and one flask shaped formed in homogeneous granite (Type 5b; Figure 5). Both Type 5a pits are in essence canoe gnammas (torpedo shape on surface, vertical walls leading to a flat floor), but their downward weathering has encountered a horizontal joint and this has been enlarged to create an underground cavern. The flask gnamma (Type 5b) would have started as a Type 2 cylindrical gnamma, but further weathering underground has enlarged it to a wider base below a narrower neck. Both of these types are due to special circumstances. Maclaren's (1912) view that gnammas are typically flask shape is not supported by this study.

The last nine gnammas look like other gnammas, the lotic potholes (Type 6; Figure 5) look like blunt canoes, and the plunge pools (Types 7a and 7b; Figure 5) look like cylindrical gnammas, although neither are formed by rock solution, but by moving water and its bedload. Most examples of both types have uneven bottom profiles in that they are deeper at the rear than at the overflow. Also generally both types lie on the steeper slopes of rock outcrops or near their base under a steep slope. Type 6 pits lie on a distinct stream, usually along a joint (Figure 2f), while Type 7a pits lie on an intermittent flow pathway (Figure 2g). The Yanneymooning pit (Type 7b; Figure 2h) is unusual in that it has the character of Type 7a, but is not presently on a waterway. However, there are indications upslope of a past waterway, so it is suggested it is a fossil plunge pool. As such, neither type has been reported on rock outcrops before in Australia. It could be argued that neither are gnammas in that they are not due to rock solution, but by flowing water. However both occur in granite outcrops along with other gnamma types, both are relatively deep and retain water for long periods Furthermore they contain similar aquatic invertebrates as in other pit gnammas, though diversity is severely restricted in the lotic potholes, no doubt due to occasional fast throughflows (B V Timms in prep.).

Each of these 10 types is distinguishable in plan and/ or profile (Figure 5) and sometimes by their position on a granite outcrop or their D:W ratio. There are two basic modes of origin: chemical weathering and removal of rock in solution, and rock corrasion due to erosion by running water and its bedload. Types 1–5 owe their origin to rock weathering, each a minor variation on the theme championed by Twidale & Corbin (1963). Types 6 and 7 are unusual, though of course typical of many waterholes on stream courses on hard homogeneous substrates

There are at least two other types of Australian deep gnammas not encountered in this study. One is the armchair hollow, generally on side slopes of an exposed rock outcrop. Two examples are illustrated in Bayly (2011 p. 50, 53), and Twidale & Corbin (1963) provided a picture and two diagrams. These have a steep rear and side walls, and either a flat floor (and hence maybe a type of pan gnamma) or a deeper pit. According to Twidale & Corbin (1963) they develop by loss of the indurated surface and then asymmetrical weathering of the exposed rock to perhaps form a cavern. These authors then proposed that the rear and side walls are smoothed by water washing downslope. This may be so, but based on the my observations of Victorian gnammas, the hollow formed may be caused by differential weathering because of crystalline imperfections. Clearly more study

is needed on armchair gnammas. While some armchairs occur in the study area (e.g. on the Humps: Twidale 1971) I could not find any with a pit holding water.

The second type of pit gnamma occurs in desert topography generally in lateritic rocks further east of the Wheatbelt and Goldfields in the Victoria and Gibson Deserts. It has been termed a pipe gnamma (Bayly *et al.* 2011) because most are narrow deep pits (D:W>>1) and claimed to be formed by dominantly vertical weathering. Walls are rough due to included rock pieces in the laterite, and not smooth as in most granitic pit gnammas. Hence they are similar in structure to the present Type 2 cylindrical gnammas, but are not in granite and have particularly high D:W ratios. Further study of them is needed.

ACKNOWLEDGEMENTS

I appreciate the directions to gnammas in the Beacon area by John and Marilyn Dunn and Brian and Marian Kirby, in the Mukinbudin area by Robert and Whispie Bayly and Russell Sache, in the Hyden area by Sheenagh Collins, Robbie Trenorden, Rolf Meeking, Garath Walton and Langdon Bristow-Baohm, and in the Norseman area by Mark Coleman and Bindy Datson. I am indebted to Ian Bayly who directed me to the wonderful set of pit gnammas on Twine Rock and to Phil Lewis who introduced me to Derdibin pit gnamma and arranged its rehabilitation. Thanks are due to the field assistants (Nathan Gazsik, Wendy Timms, Melanie Timms and John Vosper) for help on various trips. I also thank the Kirbys, Baylys and Trenordens for hospitality in the Wheatbelt and Mark and Bindy for providing me a happy headquarters in Perth. I am indebted to Ian Elliott and Ian Bayly who helped with literature and also Ian Bayly for helpful comments on the manuscript and to Colin Pain and Dennis Netoff who reviewed the final manuscript.

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Received 1 May 2013; accepted 11 June 2013

APPENDIX 1 LOCATION, SIZE AND TYPE OF PIT GAMMAS

No	Name	Nearest town	Coordinates	Width (m)	Depth (cm)	Ratio D:W	Volume (m^3)	Type
1	Derdibin[a]	Wyalkatchem	31°20'25"S, 117°20'04"E	5.5 x 3.5	~300	0.66?	23.86	1b
2	Oak Flat East	Goomalling	31°08'20"S, 116°52'49"E	2.5 x 2.1	80	0.35	1.66	1b
3	Oak Flat West	Goomalling	31°08'21"S, 116°52'46"E	2.6 x 2.1	90	0.38	1.95	1b
4	Dingo	Wongan Hills	30°51'43"S, 116°58'28"E	2.7 x 2.0	67	0.29	1.39	1a
5	Miamoon	Wubin	30°09'08"S, 116°28'45"E	~3.5 x 3.3	40	0.11	1.82	1b
6	War	Morawa	29°04'37"S, 115°59'51"E	6.4 x 3.2	120	0.25	9.60[e]	3
7	Trayning Far Southwest	Trayning	30°59'29"S, 117°50'46"E	2.8 x 2.8	105	0.37	3.23	1b/3
8	Trayning Southwest	Trayning	30°59'29"S, 117°50'46"E	1.6 x 1.1	85	0.63	0.61	1b/3
9	Trayning Mid[a]	Trayning	30°59'29"S, 117°50'47"E	1.3 x 1.0[b]	~100[b]	0.87	0.52	1b/3
10	Trayning Northeast	Trayning	30°59'28"S, 117°50'47"E	2.7 x 1.3[b]	95[b]	0.48	2.56[d]	3
11	Trayning Far Northeast	Trayning	30°59'28"S, 117°50'47"E	2.3 x 0.8	60	0.39	0.82[d]	3
12	Cadigan South[a]	Bencubbin	30°46'54"S, 117°52'22"E	1.15 x 1.05	230	2.09	1.09	2
13	Cadigan Mid[a]	Bencubbin	30°46'54"S, 117°52'22"E	1.7 x 1.7	380	2.23	4.31	2
14	Cadigan North[c]	Bencubbin	30°46'53"S, 117°52'22"E	0.95 x 0.5	65	0.89	0.10	3
15	Wondoning Hill	Beacon	30°34'36"S, 118°04'43"E	3.2 x 1.4	49	0.21	0. 94[e]	4
16	Alkiri South	Beacon	30°23'59"S, 117°55'54"E	2.8 x 1.5	50	0.23	0.91	1a
17	Alkiri North[c]	Beacon	30°23'59"S, 117°55'54"E	0.9 x 0.85	92	1.05	0.28	1a
18	Yellari South	Beacon	30°19'44"S, 117°49'58"E	3.7 x 3.1	135	0.40	6.12	1b
19	Yellari North	Beacon	30°19'44"S, 117°49'58"E	0.8 x 0.8[b]	48[b]	0.60	0.12	1b
20	Herndermoning South	Beacon	30°15'23"S, 116°58'29"E	3.6 x 3.5	80	0.22	3.96	1b
21	Herndermoning North	Beacon	30°15'23"S, 116°58'29"E	1.3 x 1.25	57	0.36	0.45	1b
22	Granite Creek	Beacon	30°14'20"S, 117°49'08"E	4.6 x 1.1	56	0.20	1.41[e]	3
23	Washington South	Beacon	30°09'06"S, 117°34'41"E	~12 x 8[b]	115[b]	0.12	45.16	1a
24	Washington Northwest[c]	Beacon	30°08'52"S, 117°34'46"E	2.1 x 1.0	58	0.37	0.17	1a
25	Washington Northeast[c]	Beacon	30°08'57"S, 117°34'41"E	1.5 x 1.1	38	0.29	0.25	1a
26	Remlap North[a]	Beacon	30°02'04"S, 117°37'50"E	4.7 x 3.8	105	0.25	7.45	1a
27	Karroun Hill South	Beacon	29°59'43"S, 118°10'44"E	1.25 x 1.2	85	0.50	0.69	2
28	Karroun Hill North	Beacon	29°59'43"S, 118°10'44"E	1.5 x 1.45	87	0.74	0.59	2
29	Bullamanya South[a]	Paynes Find	29°09'53"S, 117°39'36"E	2.5 x 2.3	60	0.25	1.36	7a
30	Bullamanya North[a]	Paynes Find	29°09'52"S, 117°39'36"E	3.8 x 3.1	72	0.21	3.36	7a
31	Bullamanya Upper[a]	Paynes Find	29°09'51"S, 117°39'37"E	1.5 x 1.2	55	0.39	0.41	7a
32	Walga	Cue	27°24'09"S, 117°27'48"E	2.5 x 1.4	95	0.49	1.42	1b
33	Weira	Mukinbudin	30°59'54"S, 118°23'13"E	8.5 x 5.0	150	0.22	26.84	1b
34	Isoetes	Mukinbudin	30°54'11"S, 118°33'20"E	2.7 x 0.8	53	0.30	0.20	6
35	Quanta Cutting	Mukinbudin	30°51'49"S, 118°25'46"E	6.5 x 4.8	90	0.16	11.28	1b
36	Wattoning	Mukinbudin	30°46'11"S, 118°11'14"E	1.5 x 0.45	105	1.08	0.35	5a/3
37	Willogyne South	Mukinbudin	30°45'59"S, 118°16'27"E	8.5 x 5.5	80	0.10	15.39	1b
38	Willogyne North	Mukinbudin	30°45'59"S, 118°16'27"E	5.5 x 4.5	145	0.29	14.24	1b
39	Yanneymooning	Mukinbudin	30°43'04"S, 118°33'24"E	1.9 x 1.0	53	0.37	0.44	7b
40	Melancobbing	Mukinbudin	30°40'12"S, 118°32'21"E	~8.0 x 8.0	90	0.11	22.62	1b
41	Beringbooding Southwest	Mukinbudin	30°33'38"S, 118°29'35"E	7.25 x 4.5	175	0.30	7.55	1a
42	Beringbooding North	Mukinbudin	30°33'31"S, 118°29'42"E	12.0 x 12.0	>200	0.22?	>110.00	1b
43	Old Rainey	Menzies	29°43'24"S, 119°37'42"E	2.4 x 1.9	45	0.82	0.21	1b
44	Johnson	Menzies	29°48'11"S, 119°49'29"E	2.05 x 1.0	88	0.80	0.83[d]	3
45	Roe	Mt Walker	31°59'37"S, 118°48'40"E	3.8 x 1.2	62	0.25	1.52	6
46	Twine Far North	Mt Walker	32°06'26"S, 118°57'22"E	4.6 x 2.2	46	0.63	0.14	6
47	Twine North	Mt Walker	32°06'34"S, 118°57'27"E	1.05 x 1.0	85	0.83	0.35	7a
48	Twine Mid	Mt Walker	32°06'51"S, 118°57'27"E	2.8 x 1.8	95	0.41	4.05	1a/3
49	Twine Shrub[a]	Mt Walker	32°06'53"S, 118°57'27"E	2.5 x 1.4	195	1.00	2.91	3
50	Twine Southeast[a]	Mt Walker	32°06'53"S, 118°57'28"E	2.7 x 1.45	80	0.39	2.70[d]	3
51	Twine Southwest[a]	Mt Walker	32°06'53"S, 118°57'27"E	2.5 x 1.8[b]	57[b]	1.03	0.27	1a/3
52	Twine Borehole	Mt Walker	32°06'53"S, 118°57'27"E	0.85 x 0.5	31	0.50	0.06	2
53	Anderson	Hyden	32°10'12"S, 118°51'26"E	1.2 x 1.2	38	0.21	0.32	1a
54	Humps North	Hyden	32°18'41"S, 118°57'37"E	1.7 x 1.7[b]	76[b]	0.45	0.86	1a
55	Humps South	Hyden	32°18'46"S, 118°57'38"E	1.0 x 0.6	100	1.20	0.50[d]	3
56	Meeking[c]	Hyden	32°12'53"S, 119°05'04"E	1.05 x 0.6	55	0.67	0.15	1b
57	Wheelers[c]	Hyden	32°19'59"S, 119°17'10"E	0.5 x 0.45	42	0.88	0.04	1a
58	Baohm	Hyden	32°21'34"S, 119°12'02"E	1.5 x 1.15	64	0.48	0.44	1b
59	Horse Collar	Kulin	32°48'04"S, 118°23'34"E	1.5 x 0.75	50	0.24	0.44?	5a/3
60	Forestiana South[c]	Hyden	32°24'42"S, 119°12'03"E	0.5 x 0.4	84	1.86	0.07	2
61	Forestiana North	Hyden	32°24'42"S, 119°12'03"E	1.0 x 0.3	34	0.52	0.06	2
62	Lilian Stokes Far South[a]	Lake King	33°04'06"S, 120°05'49"E	0.20 x 0.18	66	3.47	0.01	5b
63	Lilian Stokes South	Lake King	33°04'06"S, 120°05'49"E	1.6 x 1.0[b]	58[b]	0.38	0.45	1a
64	Lilian Stokes North	Lake King	33°04'06"S, 120°05'49"E	1.2 x 0.9[b]	40[b]	0.17	0.38	1a

APPENDIX 1 (cont.)

No	Name	Nearest town	Coordinates	Width (m)	Depth (cm)	Ratio D:W	Volume (m^3)	Type
65	Lilian Stokes Far North[a]	Lake King	33°04'06"S, 120°05'49"E	0.25 x 0.2	70	3.11	0.01	2
66	Victoria Rock	Coolgardie	31°17'37"S, 120°51'48"E	1.8 x 1.45	61	0.38	1.72	1b
67	Cave Rock	Widgiemooltha	31°39'40"S, 121°13'38"E	1.4 x 0.9	56	0.49	0.29	6
68	Higgensville Far North	Norseman	31°44'41"S, 121°34'08"E	~15.0 x 5.0	160	0.16	60.00[e]	4
69	Higgensville North	Norseman	31°44'41"S, 121°34'08"E	6.5 x 1.9	30	0.16	1.85[e]	4
70	Higgensville Mid	Norseman	31°44'41"S, 121°34'08"E	2.7 x 1.1	50	0.26	1.21[d]	3
71	Higgensville South	Norseman	31°44'41"S, 121°34'08"E	1.3 x 0.5	60	0.67	0.27[d]	3
72	Higgensville Southwest[c]	Norseman	31°44'41"S, 121°34'07"E	1.65 x 0.55	50	0.43	0.33[d]	3
73	Theatre Far North	Norseman	32°08'23"S, 121°33'23"E	4.6 x 3.1[b]	54[b]	0.16	3.14	1b
74	Theatre North	Norseman	32°08'23"S, 121°33'23"E	0.6 x 0.4	30	0.60	0.05[d]	3
75	Theatre South[c]	Norseman	32°08'24"S, 121°33'22"E	0.95 x 0.45	45	0.64	0.14[d]	3
76	Theatre Far South	Norseman	32°08'25"S, 121°33'22"E	2.7 x 2.6	65	0.25	1.79	1b
77	Buldania East	Norseman	32°07'56"S, 120°55'38"E	2.7 x 2.6	90	0.34	2.48	1a
78	Buldania South	Norseman	32°07'56"S, 120°55'38"E	2.05 x 1.1	44	0.28	0.43	1a
79	Buldania West	Norseman	32°07'56"S, 120°55'37"E	3.0 x 2.5	67	0.24	1.99	1a
80	Balladonia[a]	Norseman	32°27'41"S, 123°51'48"E	6.3 x 0.45	65	0.19	1.13[e]	4

[a] cleaned out in 2010 summer.
[b] floods to greater area and depth.
[c] capped.
[d] rectangular formula used for volume calculation.
[e] triangular profile formula used for volume calculation.

Mechanism and effects of silencing green peach aphid genes via RNA interference *

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When chemicals are used to control insect pests, the potential for resistant phenotypes to develop is well documented. Genetically modified plants expressing a bacterial protein (Bt) are now widely deployed, but are only effective against chewing insects. There is now an opportunity to exploit the highly conserved natural cellular process of RNA interference (RNAi) to silence specific genes in sucking insects such as aphids. RNAi can be triggered when double-stranded RNA (dsRNA) is introduced into a cell where a series of cellular processes lead to unwinding of the RNA and binding to a complex which degrades a target mRNA, leading to loss-of-function of its protein.

The aim of this research is to investigate the mechanism and effects of silencing essential genes of the green peach aphid (*Myzus persicae*). To identify target genes for the project, we will employ comparative genomics and bioinformatics tools to identify and characterise green peach aphid orthologues of genes essential for development using the expressed sequence tags of green peach aphid, the genomic data available for the related pea aphid, *Acyrthosiphon pisum* as well as genomic resources of the best-annotated multicellular organism to date, *Caenorhabditis elegans*. Selected genes would be characterised *in silico* using, for example, the functional genomic resources that details RNAi phenotypes of almost all known genes of the free-living nematode, *C. elegans*. In addition, genes encoding proteins secreted from the salivary glands (the secretome) would be characterised using RNAi by investigating their effects on the viability and reproduction of aphids when they are silenced. Currently, we have amplified and sequenced six target genes and used these to establish an *in vitro* RNAi system *via* dsRNA feeding of nymphs with artificial diet sachets containing sucrose and dsRNA corresponding to the target genes. These genes, involved in proton translocation, locomotion, olfaction and osmoregulation, share up to 90% nucleotide sequence homology with the pea aphid and have no sequence homologies with the human, mouse, *Arabidopsis* and tobacco genomes.

The mechanism of RNA silencing is not well-understood in insects. To study in detail how small RNAs are processed by insects, we will use dsRNA and small RNAs of different conformations and compositions to elicit gene silencing, and to investigate the lengths and types of sequences in constructs that produce the best RNAi response and effects on green peach aphid via *in vitro* feeding and through transgenic plants. After feeding on dsRNA, gene knockdown in nymphs will be assessed by quantitative polymerase chain reactions (qPCR) to measure transcript abundance in primary target aphids as well as in their progeny. Effects of silencing essential genes will be assessed by monitoring survival and fecundity of aphids on a host plant after feeding on dsRNA for 24 hours. This monitoring will be done at 24 hourly intervals for 16 days and the results compared with nymphs treated without dsRNA.

To evaluate the possibility of using RNAi as a control strategy for sucking insect pests, green peach aphid will be reared on transgenic plants modified to produce dsRNA corresponding to candidate RNAi genes which when silenced limit aphid reproduction and affect survival. This proof-of-concept will use model host plants such as *Arabidopsis thaliana* and *Nicotiana tabacum*. The results of this research will provide target genes that effectively disrupt development, reproduction and survival of green peach aphid, and lay a foundation for RNAi-mediated control of not only green peach aphid but many of the world's damaging aphid and insect pests.

* Extended abstract of a paper presented at the Royal Society of Western Australia Postgraduate Symposium 2012 held at Curtin University on 29 September 2012.

Distribution, abundance and bioerosion of the grazing sea urchin *Echinometra mathaei* at Ningaloo Marine Park, Western Australia *

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Sea urchins can have a significant influence upon the ecological structure of coral reefs through both bioerosion of substrata and by affecting competition for space. Loss of reef structure can limit space for algal and coral recruitment which further alters the balance between reef growth and reef destruction. Urchins are important grazers in many marine systems and can cause major ecosystem changes when their numbers reach high levels (generally after a decline in the numbers of their fish predators). However, the relative importance of the role of urchins in influencing the composition and structure of coral reef habitats has rarely been explored. This study investigated the habitat preferences, distribution, grazing, bioerosion and behaviour of the grazing urchin *Echinometra mathaei* at Ningaloo Marine Park, Western Australia. Coral reef habitats of the Ningaloo Marine Park were characterised using field surveys and validations of broad-scale hyperspectral benthic habitat maps; the effects of habitat type and different closure regimes (e.g. Sanctuary zones) on urchin distribution and abundance were then examined and compared. This is the first study to quantify the grazing and consequent bioerosion rates of *E. mathaei* at Ningaloo Reef and the first to study their animistic behaviour and diurnal movement patterns.

Data were collected from over 100 sites within the marine park, focusing on nearshore, lagoonal and backreef areas within Sanctuary zones and adjacent Recreation zones. Data analyses indicated that the distribution of urchins was variable and appears not to be affected by the management zones of the park (i.e. no significant evidence has been found of indirect effects from fishing of known urchin predators). However, habitat type had a major influence on urchin distribution: urchin abundances were higher on nearshore intertidal and subtidal reef platforms, lagoonal patch reefs and shallow backreef platforms than in other habitats. Data analysis showed strong positive correlations between urchin densities and habitats that contained turf algae, and a combination of limestone pavement and turf algae.

Grazing and bioerosion studies demonstrated that although *E. mathaei* grazing plays an important ecological role, concomitant bioerosion may play a more central role in influencing the structure of coral reef communities than grazing at the Ningaloo Marine Park. Urchin morphometrics and gut content analyses from different habitats in four regions of the Ningaloo Marine Park indicated higher mean urchin densities, size and subsequent bioerosion rates in southern regions than in the north of the park. Bioerosion rates from Ningaloo Reef (1.0–4.5 kg m^{-2} $year^{-1}$ of $CaCO_3$) were found to be comparable to degraded (overfished) reef systems in other parts of the world, but without accurate estimates of $CaCO_3$ accretion rates it is difficult to determine the degree to which bioerosion is affecting reef growth at the Ningaloo Marine Park or if it is any more or less significant than in other parts of the world. Results from this study suggest that habitats at Ningaloo with high *E. mathaei* densities are more likely to be niche habitats that coexist with other coral reef habitats as part of a healthy ecosystem.

Video footage of diurnal movement revealed that *E. mathaei* did not leave their burrows to graze but were systematically 'gardening' turf within longitudinal burrows at night and sheltering from predators during the day. Observations of animistic behaviour experiments showed that they would also defend their burrows when threatened by intruding conspecifics but the majority of interactions would result in urchins coexisting in the same longitudinal burrow. This type of territorial grazing behaviour within long, tube-like burrows has been documented for other urchin species (e.g. the northern Atlantic echinoid, *E. lucunter*) but never for *E. mathaei*. Defence of (and sharing of) longitudinal burrows may also be associated with other predation avoidance behaviour.

ACKNOWLEDGEMENTS

MWL wishes to thank his PhD supervisors Mike van Keulen (Murdoch University) and Erik Paling (Sinclair Knight Merz); research assistants Fionna Cosgrove and Kimberly Marrs-Ekamper; Frazer McGregor and Lauren Jakson at Coral Bay Research Station; staff from DEC Exmouth; Murdoch University, Neil Loneragan and the CSIRO Wealth from Oceans Ningaloo Collaboration Cluster for financial support.

* Extended abstract of a paper presented at the Royal Society of Western Australia Postgraduate Symposium 2012 held at Curtin University on 29 September 2012.

Journal of the Royal Society of Western Australia, 96: 21–22, 2013

Palynology of the southern Gunbarrel Basin *

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The Narnoo Basin is a small intracratonic basin in the southwest region of the Gunbarrel Basin adjacent to the northeast margin of the Yilgarn Craton in Western Australia (Fewster 1999). The basin is currently being explored for uranium with gold and heavy base-metals having already been discovered. The current exploration program, commenced in 2007 by Energy and Minerals Australia (EMA), centres on the Mulga Rocks deposits. To date, four separate zones of uranium mineralisation have been delineated, all of which are associated with a paleochannel. At present only preliminary lithostratigraphic schemes are in use for sediments younger than Cretaceous age and these are constrained to localised areas around mineral deposits. Correlation using this informal system is proving inadequate as further drilling is completed. With no age constraint, the informal units proposed by EMA are difficult to correlate.The aim of this research program is to resolve issues associated with the lateral continuity of units, the age of the basement rock intersected during both recent and previous (1970s Petroleum and Nuclear Corporation Exploration Pty Ltd), drilling programs, and the significance of faulting across the Narnoo Basin.

The successful use of biostratigraphy, in particular palynology, in correlating similar sediments in the Gippsland Basin, southern Victoria (Stover & Partridge 1973), has led to the proposal that similar techniques be applied to the Narnoo Basin. The lack of appropriate lithology which can be used for radiometric dating and the lack of recognisable marine incursions in the Narnoo Basin indicate that palynology is the best method available for the correlation of these strata. Palynological analyses involve the identification and abundance of pollen and spore species present in the rock record. As the vegetation changes within an area, the pollen assemblages preserved record these temporal changes. In addition to potentially being able to date these sections, palynology will also facilitate a study of the paleovegetation, which involves the reconstruction of flora through geological history. This is particularly important as research has indicated that the species present in Western Australian Cenozoic sediments are remarkably different when compared to eastern Australian assemblages of similar age (Milne 1988). Little Cenozoic palynological work has been done in southwestern Australia to date as compared to eastern Australia, and there are no Western Australian biozones for this time.

Samples collected for palynological analysis (Mack 2011) were processed using hydrofluoric (HF) and hydrochloric (HCl) acid to remove the mineral content and nitric acid (HNO_3) and sodium hydroxide (NaOH) to oxidise extraneous organic material (Phipps & Playford 1984). So far, a total of 186 species of cryptogam spores and angiosperm and gymnosperm pollen have been recovered from 16 samples (Mack 2011). Of these 102 are new species that have not been described in previous Australian work, and are mainly *Tricolpites* spp, *Rhoipites* spp, *Tricolporites* spp and *Proteacidites* spp. The general characteristics of these assemblages are distinctly Eocene with several species conformable with the Middle *Nothofagidites asperus* Zone of the Gippsland Basin (Stover & Partridge 1973) and its equivalent in the Murray Basin, dated as late Eocene (Macphail 1999). A further 120 samples have been collected for this current study.

It is projected that correlation of the stratigraphic units established by EMA with units intersected by other companies operating in the area will assist further exploration and the discovery of new uranium deposits. Analysis of the palynomorph assemblages recovered will include: description of new species, delineation of biostratigraphic zones, palynostratigraphic correlation of units of the Narnoo and Gunbarrel Basins, and construction and comparison of pollen assemblage distribution charts for the Gunbarrel, Eucla and Bremer Basins. Thiswill provide the foundation for a high-resolution spore–pollen biostratigraphic framework for the Western Australian Cenozoic sediments. Biostratigraphy utilising palynology has proved highly successful for the correlation of sediments and is recognised as an essential tool in the petroleum, mineral and groundwater exploration industries.

In addition to biostratigraphic correlation, comparison of the pollen and spore assemblages recovered from Narnoo Basin core with assemblages from the western Eucla and Bremer Basins will provide a better understanding of southwestern Australian Cenozoic paleovegetation. Comparison of fossil species with modern pollen and spores will determine their likely botanical affinity and the implications of these relationships for paleoenvironment reconstruction. Relation of southwestern paleovegetation with studies completed in southeastern Australian Cenozoic basins will allow for investigation of the evolution and differentiation of flora across southern Australia during the Cenozoic, and its response to local and global environmental change that is important in today's changing environment.

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* Extended abstract of a paper presented at the Royal Society of Western Australia Postgraduate Symposium 2012 held at Curtin University on 29 September 2012.

ACKNOWLEDGEMENTS

I would like to acknowledge: my Honours supervisor, and PhD co-supervisor, Lynne Milne for envisioning this project and her contributions to my understanding of palynology; the ongoing help and support of my supervisor Associate Professor Kate Trinajstic; and Energy and Minerals Australia for providing material for study including samples, cross-sections and maps of the study area, field work and funding the project.

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Nutritional risk in children with cystic fibrosis is associated with reduced lung function, pancreatic insufficiency and gender *

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BACKGROUND

Nutritional status is correlated with lung health and disease severity in cystic fibrosis patients and is an independent predictor of mortality. Cystic fibrosis patients may have impaired pancreatic and intestinal function resulting in malabsorption of fat-soluble vitamins and reduced nutritional status. No previous data has been published pertaining to the Western Australian cystic fibrosis population. As Princess Margaret Hospital is the sole paediatric cystic fibrosis care centre for Western Australia, it represents the entire cystic fibrosis population of Western Australia. This study describes the cystic fibrosis population of Princess Margaret Hospital in terms of nutrition risk, lung function, rate of hospitalisation and fat-soluble vitamin status and examines the associations between these factors.

METHOD

A cross-sectional, retrospective medical record audit was undertaken of 162 children diagnosed with cystic fibrosis in Western Australia and admitted to Princess Margaret Hospital. Gender; age; height (cm); weight (kg); number of hospitalisations over 12 months; serum fat-soluble vitamins levels (vitamin A: serum retinol; serum 25 hydroxy vitamin D; vitamin E: serum α-tocopherol, vitamin K: serum prothrombin); pancreatic function (sufficient/insufficient); and lung function (forced expiratory volume [FEV1%]) were collected. Patient nutritional risk was calculated based on BMI percentile and change in weight and categorised as High Nutrition Risk, At Nutrition Risk, Not At Nutrition Risk. χ^2 analysis and one-way ANOVA were used to determine the relationship between risk category and categorical variables (gender and pancreatic sufficiency) and continuous variables (lung function, age, fat-soluble vitamins) respectively.

RESULTS

We determined that 20% (n=32) of the Princess Margaret Hospital cystic fibrosis population were at High Nutrition Risk, 9% (n=15) were At Risk and 71% (n=113) were Not At Risk. There was a significant difference in distribution of gender across the nutrition categories (χ^2 =8.37, P=0.015). Patients classified At Nutrition Risk or High Nutrition Risk (29.4%) were more likely to be female (21%) than male (13%). Seventy-five per cent (n=24) of the subjects in the High Risk category and 66% (n=10) of the subjects in the At Risk category were female. The number of males and females in the Not At Risk category was not significantly different. The mean ages of patients in the High Risk and At Risk categories were greater than those in the Not At Risk Category (F=5.032, P=0.008).

The mean FEV1% was 97.3% (SD 16.1). Patients in the High Risk (87±13%) and At Risk (89±13%) categories had a significantly reduced score when compared to the patients in the Not At Risk category (102±15%, F=10.68, P=0.001). Those in the High Risk or At Risk categories were more likely to have pancreatic insufficiency and reduced lung function when compared to those in the No Risk category. There was no significant difference in the mean levels of fat-soluble vitamins between nutrition risk categories. A χ^2 test of the mean number of hospitalisations over the past 12 months showed no significant difference between nutrition risk categories.

Serum vitamin retinol levels were within the reference range for 87% of subjects, below range for 5% and above range for 8%. Serum 25 hydroxyvitamin D levels were below the cut off (>75 nmol/L) for 57% of subjects and within range for 43%. Levels of α-tocopherol were above the reference range (7–30 nmol/L) in 29% of subjects, within range for 71% and below range for 6%. Prothrombin times were within range (12.3–18 seconds) for 89% of subjects, with 9% below range and 2% above.

CONCLUSIONS

These data confirm an association between nutrition risk and gender, age, pancreatic insufficiency and reduced lung function in the Western Australian cystic fibrosis population. The prevalence of nutrition risk was lower than anticipated but higher among females and those who were older. Those categorised as High Nutrition Risk had a lower lung function and more likely to have pancreatic insufficiency. Further exploration into the reasons for these differences should be undertaken. Patients in the High Nutrition Risk and At Nutrition Risk populations may benefit from increased provision of dietetic intervention.

No association was found between fat-soluble vitamin status and the health outcomes measured, although the

* Extended abstract of a paper presented at the Royal Society of Western Australia Postgraduate Symposium 2012 held at Curtin University on 29 September 2012.

high prevalence of vitamin D deficiency should be acknowledged and additional vitamin D supplementation should be commenced. This could be achieved in addition to the current supplementation regimen or may be grounds for the reformulation of the current supplement used. Further exploration of vitamin K status may be indicated as combined vitamin D and K deficiency may increase the risk of poor bone mineralisation and osteoporosis in the population. Further study on the bone density of this population with regard to vitamin D and K status is recommended.

Journal of the Royal Society of Western Australia, 96: 25–26, 2013

The birds and the bees and the Banksia mating trees: measuring the success of Banksia woodland restoration using genetic and ecological markers *

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The major threatening processes to natural ecosystems globally are anthropogenic, through changes in land use and degradation. A key strategy to address these damaging processes is to implement ecological restoration programs. Ecological restoration involves the repair or creation of biological communities, ideally representative of the composition, diversity and functionality of the pre-disturbance habitat. The international community recently committed to a new target to restore 15% of degraded ecosystems worldwide by 2020 (Convention on Biological Diversity 2010). The rapid growth of the restoration industry is evident, and is currently estimated to be a $2 trillion industry worldwide. To date, most endeavours have focused on restoring vegetation and habitat structure. Consequently, restoration success has been measured against achievements in the structural properties of ecosystems. Although pollination is a critical ecosystem service, it is yet to be fully investigated or taken into account in evaluations of restoration success (Ritchie & Krauss 2012). Ultimately the fate of restored plant populations depends on restoring or preserving their mutualistic pollinator relationship.

This study is based in the southwest of Western Australia, one of the most biologically diverse yet highly fragmented and disturbed landscapes worldwide. Only 30% of the *Banksia* woodlands on the Swan Coastal Plain remain and the decline has been most marked in the last 20 years. Southwest Western Australia has the highest proportion of bird-pollinated native plants and pollinator diversity in the world (Phillips *et al.* 2010) and their importance for outcrossing and production of genetically robust outbred seed is well known. Predicting and managing the effects of human-induced habitat disturbance is particularly challenging for organisms that rely on interactions with other species for services such as pollination and dispersal (Menz *et al.* 2011), and there is increasing evidence that human disturbance negatively impacts plant–pollinator interactions. The implications of these interactions for restoration success are yet to be fully investigated.

The main objective of this research is to conduct a genetic and ecological assessment of restoration success, by assessing population levels of genetic diversity, structure, mating patterns, connectivity and delivery and diversity of pollinator services in two keystone *Banksia* woodland species. In order to evaluate how well we are achieving ecological restoration, we will examine how seed sourcing impacts the genetic diversity of a restored population, if the products of mating among individuals reflect that of undisturbed ecosystems, and how might these interactions affect the long-term viability and functionality of restored populations. These parameters will be assessed and compared within restored populations and their offspring to those adjacent natural, fragmented and undisturbed natural populations.

Both *Banksia* species (*Banksia attenuata* and *Banksia menziesii*) are preferentially outcrossing and obligately outcrossing with mixed generalist pollination systems, being pollinated by nectar-feeding birds (predominantly honeyeaters in the family Meliphagidae), native bees, wasps and introduced honey bees (*Apis mellifera*). It is vital that the plant–pollinator interactions are restored and with their pollination systems, they are most likely to be impacted by changes in pollinator visitation and movement.

Specific aims of the research are: (i) identification of genetic diversity structure and mating system parameters of *B. attenuata* and *B. menziesii* using microsatellites markers, in restored, natural fragmented and natural unfragmented (control) populations; (ii) assessment of the diversity and abundance of pollinators in restored and natural populations; (iii) characterisation of pollen dispersal for *B. attenuata* and *B. menziesii*, assessing the delivery of pollinator services within and between restored and natural populations through genetic paternity assignment and pollinator observations; and (iv) assessment of the importance of adjacent natural fragments for the ecological restoration success of *Banksia* woodlands.

Genetic methods will be employed to estimate levels of outcrossing, determine paternity and mating systems by assessing the genetic structure of seeds developed from open-pollination. Determining paternity will allow detection of pollen movements and therefore the distances pollinators travelled. However, it is difficult to identify pollinators using molecular data alone therefore pollinator mutualisms will be examined through observing pollinators and their movements in the field.

Patterns of pollen flow and the delivery of pollinator services are directly related to pollinator behaviour, species and relative abundance. Therefore, the relative

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abundance and foraging behaviour of pollinators will be assessed and compared between populations using floral observations (four replicates/population/season) and Malaise tents (six replicates/population/season, collecting flying invertebrates) over three years. As the presence of invertebrate pollinator species may not reflect pollinator efficiency, insect-collected pollen from Hymenoptera will also be examined.

Few studies have evaluated restoration success. This study is one of the first to assess the restoration of functionality. It will provide a solid genetic basis for future restoration and conservation work to better understand the driving mechanisms behind mating systems, pollinator mutualisms, and how these are affected by anthropogenic disruption.

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Book Review

A Beginners Guide to Diatoms

A Beginners Guide to Diatoms by Jacob John

Gantner Verlag Liechtenstein, 2012. 150 pages, 77 plates with 305+ colour and black & white photos; paperback. ISBN 9783905997125

Jacob John is considered the foremost expert of diatoms in Australia and it is through decades of research into diatom taxonomy and ecology that *A Beginner's Guide to Diatoms* has been produced. *A Beginner's Guide to Diatoms* is a taxonomic guide that aims to educate novices on all aspects of diatom research from slide preparation to key morphological features.

Diatoms are effective indicators of wetland health, but advancing to the level of species identification requires an understanding of basic diatom morphology, which is what this guide aims to achieve. Recognising the scarcity of guide books on basic diatomology, John's current contribution targets an audience in education and research, in particular those who may not be formally trained in diatom taxonomy or phytoplankton sampling.

A Beginner's Guide to Diatoms is a simplified taxonomic guide where 102 genera from fresh to saline waters are described and illustrated. With only a few references to Western Australia, the book is suited to an international audience and is valuable foundation resource for anyone wanting to study diatoms in Australia.

Overall, the guide is relevant to a current need and provides a good introduction to diatomology. As an instruction manual, it is short and concise with only four chapters. With the target audience in mind, the text is clearly presented. Key terminology is written in bold and a glossary of descriptive terms is accompanied by well-labelled diagrams, both of which will aid in student learning. Colour photographs of field sampling are aligned with both light and electron micrographs to show the sequence of events from field collection to laboratory processing, and finally to identification using both light and electron microscopy.

Chapter 1 introduces the reader to the essential skills required to collect, process and identify diatoms. The permanent preparation section reads as a step by step guide for instructors, enhanced with images from the author's laboratory. Environmental officers will find the section on sampling methods useful. The health and safety considerations when preparing slides through acid digestion is important advice from the author, especially considering that the guide is written for an audience starting out in diatom research.

Chapter 2 covers biology and the application of diatoms in forensics, biomonitoring and paleoecology. The chapter provides only a brief account of diatom use, which is my only criticism of this guide. It is clear that the objective of this book is to provide a foundation for the study of diatoms, therefore the reasons for studying diatoms should have been more substantial to engage and inspire the reader. In particular the section on harmful diatoms, which students would find particularly interesting and water managers would access the most, could have included a list of Australian taxa and images of *Chaetoceros* and *Pseudonitzchia*. Likewise, the section on diatoms use in forensic science and paleoecology could have directed the reader to more current studies. As a result, the reader would need to source this information from other publications, so the guide cannot be viewed as a standalone book in diatom education. In spite of this criticism, John does direct the reader towards more of his extensive publications to gain further knowledge and direction.

Chapter 3 and 4 provide the working vocabulary and diagnostic descriptions. It is the content of these chapters that allows *A Beginners Guide to Diatoms* to be an effective tool in teaching the basics of diatom morphology. What is presented is a quick guide to common genera, looking at their defining characteristics and common occurrence. In Chapter 3, John forms a conceptual guide based on key morphological characteristics and uses a mind map to show how 'based on a few simple parameters, it is relatively easy and convenient to classify diatoms into genera' (p. 51). The section on recent name changes is very helpful. Chapter 4 is simplified by the lack of dichotomous keys, morphological measurement and

overdetailed descriptions, resulting in a user-friendly manual.

Right from the beginning, John describes a global appreciation for the diatoms which lends his latest publication to be more than just another identification guide. The content is educational, yet personal as John uses his own experiences to inspire a new generation of scientists into diatom research. I strongly recommend this guide for undergraduate teaching in aquatic science, and as a foundation for honours and postgraduate research. *A Beginners Guide to Diatoms* does not only provide insight into the world of diatoms, but an introduction to Jacob John's extensive research on the diatoms of Australia.

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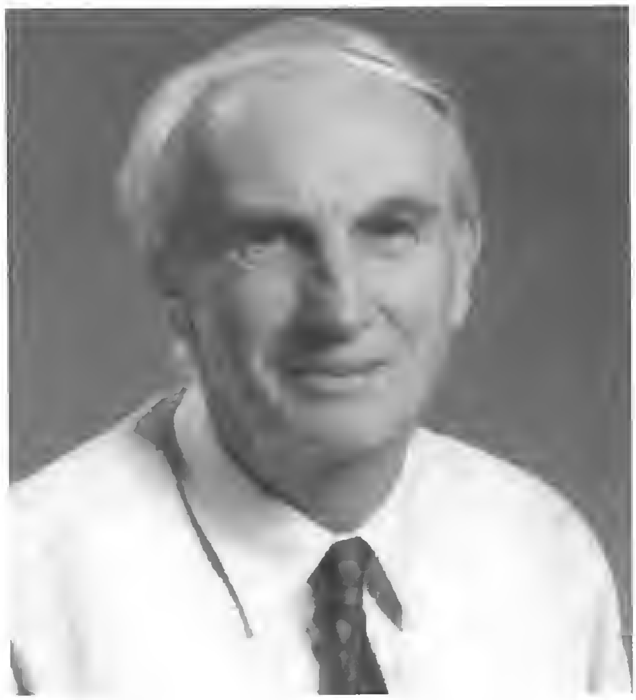
OBITUARY—JOHN ROBERT DE LAETER 1933–2010

John De Laeter was a physicist, science luminary and pillar of modern geochronology in Western Australia. He was also President of the Royal Society of Western Australia (1980–1981) and recipient of the Medal of the Royal Society of Western Australia in 1993. John helped advance science education and influenced the direction of physical sciences research in Western Australia, leading research in dating the Earth's mantle and exploring the extremities of the Solar System. Among his many scientific achievements are the measurement of the atomic weight of 12 elements and mapping the geological ages of many regions of Western Australia. His colleagues at the John De Laeter Centre for Isotope Research recently discovered the world's most ancient minerals at Jack Hills.



John De Laeter AO, PhD, DSc, BSc (Hons), BEd (Hons), DTech (hc) (Curtin), DLitt (hc) (UWA), FTSE, FAIP: 3 May 1933—16 August 2010

John began his career as a science teacher at Bunbury High School in 1959 but, at a Science Teacher's conference in Sydney, a debate on the origins of the universe inspired him to return to university to study nuclear astrophysics. After completing a PhD at the University of Western Australia (UWA) and a Fellowship in nuclear physics in Canada, he took up the position of Head of the Department of Physics at the Western Australian Institute of Technology (now Curtin University) in 1968 (aged 34), where he oversaw the commissioning of its first mass spectrometer.

John's major research interests became the application of mass spectrometry to cosmochemistry, nuclear physics, and geological problems including the containment of radioactive waste, measuring the age of rocks, evaluation of atomic weights and the origin of chemical elements. In the 1970s he established a project with the Geological Survey of Western Australia to develop a geochronology capability based on Rb–Sr decay system, and in the 1980s, with UWA now on the team, jointly developed capabilities in the areas of Sm–Nd and U–Pb geochronology.

In 1984, as Deputy Vice-Chancellor of Research and Development at Curtin University, John spearheaded a proposal for a new SHRIMP ion microprobe and SHRIMP zircon U–Pb dating became the geochronology method of choice for geologists. In 1998 the consortium received funding from the WA State Centre of Excellence Program to further develop isotope science.This saw the establishment of the John De Laeter Centre for Mass Spectrometry, recently renamed the John De Laeter Centre for Isotope Research. In the following years organic chemistry facilities were established, CSIRO joined the consortium and a second SHRIMP was commission in the Centre.

In his various administrative and educational roles at Curtin University, John negotiated with the university, businesses and State Government to invest in visionary projects that are now outstandingly successful facilities. These include Technology Park (Chair, 1988–2003, and then Patron); the Science and Mathematics Education Centre at Curtin University, the Scitech Discovery Centre (Deputy Chair, 1988–1996, and then Patron); and the Gravity Discovery Centre at Gingin (Foundation Chair).

Community positions he held included President of the Western Australian Conservation and Environment Council, Governor of the Clunies Ross Foundation and captain of an Australian veterans hockey team. He was also a Lay Preacher in the Uniting Church.

John received many awards including the Order of Australia (1992), Medal of the Royal Society of Western Australia (1993), a Fellowship of the Australian Academy of Technological Sciences and Engineering, an Honorary Doctor of Technology from Curtin University (1995). In respect of his research in astrophysics, a minor planet (Minor Planet De Laeter 3893) was named after him.

In 1995 when John retired as Curtin Deputy Vice-Chancellor of Research and Development, an international conference on Isotope Science was held to formally recognise his research achievements. The two day De Laeter Symposium on Isotope Science was held in November 1995 and attracted delegates from the European Community, the United States, Canada, Japan and Australia. Papers based on the presentations at the conference were published in a special volume of the Journal of the Royal Society of Western Australia (Vol. 79, Part 1, 1996).

John De Laeter's legacy will be perpetuated in many ways—in his large body of published works, Minor Planet De Laeter, the John De Laeter Building at Curtin University, Scitech, the Gravity Centre, the colleagues that carry on his tradition of collaborative work and the John De Laeter Centre for Isotope Research that is continually producing new techniques and data that shape our understanding of the Earth and its place in the Universe.

OBITUARY—GILLIAN PERRY (NÉE JENKINS) 1943–2011

Gillian Perry, one of Australia's foremost botanical nomenclaturists, and a former member and office bearer of the Royal Society of Western Australia passed away unexpectedly in August 2011.

Born in Perth, Gillian was the only child of two well-known Western Australian zoologists Clee Francis Howard Jenkins and Eileen Jenkins, both long-time members and office bearers of the Royal Society.

Gillian attended the University of Western Australia, graduating with a Bachelor of Science, with a major in Botany in 1967. A student of Professor Brian Grieve her initial interest was in plant physiology and after positions with the Forests Department and the University's Institute of Agriculture, she moved to research position at Macquarie University working on plant hormones. An MSc degree with a thesis on gibberellins, completed under Professor Arthur McComb, was awarded in 1974.

In 1971 Gillian returned to Perth and joined the Western Australian Herbarium, then a part of the Western Australian Department of Agriculture. Gillian's initial work, for the Flora of Australia, was on the genus *Logania*, however her interest turned to the neglected weed flora of the state and she quickly became the authority for weedy plant identification and nomenclature for the Agricultural Protection Board officers, Agricultural Advisors and farmers of the state's vast agricultural areas.

From 1973 to 1980 Gillian, and husband Michael Perry, served on the Council of the Royal Society as Joint Honorary Secretaries. This followed a long family tradition as her father Clee Jenkins is the Society's longest serving President.

Gillian's work on the weed flora of Western Australia led to a growing interest in nomenclature, the branch of taxonomy concerned with the application of plant names, and following her retirement from the Western Australian Herbarium in April 1994, she devoted the rest of her life to the pursuit of nomenclatural stability in taxonomy. An intensely private person, her role in global nomenclature was not well known but had international impact. She attended, and was active in, the Nomenclature Sections of every International Botanical Congress from 1981 to 2011, a span of 30 years.

During that time she authored or co-authored no fewer than 69 proposals to amend and clarify the Botanical Code, also serving on the Permanent Nomenclature Committee for Vascular Plants from 1999 until her death in 2011. She had a special interest in lectotypification and the recommendations of the Special Committee set up in 1987, of which she was a member, were very important in clarifying the rules on this difficult area. Gillian's many contributions were specifically recognised in the Acknowledgements of the Committees report.

The XVIII International Botanical Congress held in Melbourne in July 2011 will be remembered as historic, with three major decisions regarding botanical nomenclature: electronic publication of names, the cessation of mandatory Latin for diagnoses, and changes to the handling of fungal names. Gillian was involved in all of these. She was particularly instrumental in finding a solution and consensus to the thorniest issues involved in the latter, and for her efforts, the report of the mycological section of the congress named her an 'honorary mycologist'.

It was in returning to Perth following the Congress that Gillian died, in her sleep, at Ceduna, South Australia. She is survived by husband Michael Perry.

(Michael Perry with the assistance of Kevin Thiele and John McNeill)

OBITUARY—LINDSAY JAMES PEET 1939–2012

Lindsay Peet, geologist, real estate manager and historian died on 26 September 2012 at Sir Charles Gairdner Hospital. For the past four and a half years Lindsay battled Guillan–Barré syndrome and its side-effects that left him confined to a wheelchair.

Lindsay was educated at Hale School and the University of Western Australia where he obtained his BSc in geology. Initially he worked as a geologist in industry and subsequently joined the Geological Survey of Western Australia in 1967 as a hydrogeologist. He had started research on the fossils of the Permian Mingenew Formation as a Masters project but the call of family and the family business took him away from geology, although he retained his fellowship of the Geological Society of London. He joined the real estate firm of Peet & Company Limited and took a Diploma in Valuation and a Diploma in Real Estate Management. However, he retained his interest in scientific activities and was a Council member of the Royal Society of Western Australia from 1971 to 1984. He was a Geoscience Foundation Donor to the School of Earth and Environment at his alma mater.

In 1985 the firm of Peet merged and expanded and Lindsay left to concentrate on his love of history. After obtaining a Graduate Diploma in Applied Heritage Studies from Curtin University he became a military historian and specialist defence heritage consultant. He continued in this path for the rest of his life.

As a professional historian, Lindsay's interests ranged widely from the history of real estate development in Western Australia to the conservation of the State's defence heritage with a particular interest in military aviation. He wrote numerous academic papers, chapters and articles on Western Australian history and heritage. His research on the Kalumburu war diary involved visiting the monastery at New Norcia and he became an active and much valued Friend of New Norcia and maintained his friendship with the monks there, last visiting them only three weeks before his death.

He was active on many committees including Chairman of the Defence Heritage Committee of the National Trust (WA) and honorary Assistant Curator (Historical Aviation Research) at the RAAF Aviation Museum at Bull Creek. He was a Committee Member of the Friends of Battye Library, a member of the National Trust (WA) and the Royal Western Australian Historical Society. He also held close ties with, and was Vice President of, the Professional Historians Association (WA).

Lindsay was a passionate advocate for the preservation of Western Australian historical material, and a great friend, generous supporter, and contributor to the State's heritage collections. Over many years he enabled the purchase of important and valuable collections of original and rare material. He also contributed enormously to the State Library's published works and map collections. In April 2012 he was made a Fellow of the Library Board in recognition of his efforts and contribution to the recording, collection and preservation of Western Australia's history.

Lindsay is survived by his wife Laurel and son Julian.

(Tony Cockbain with the assistance of Margaret Triffitt and Rowena Putland)

Journal of the Royal Society of Western Australia, 96: 35–37, 2013

OBITUARY—ALEC FRANCIS TRENDALL 1928–2013

Alec Trendall '...cheese-maker extraordinaire' (photo P E Playford)

Alec Trendall died peacefully at home in Springhaven, near Denmark, after a short illness. The announcement placed in the West Australian newspaper by his family aptly describes him: 'He was a gentle man with an amazing intellect, who was a respected geologist, cheese maker extraordinaire and an eternal explorer and seeker of knowledge.'

Alec Trendall was born in Enfield, Middlesex, UK, on 8 December 1928, the youngest of a family of four, two girls and two boys. Alec's father worked at the Royal Arsenal at Enfield Lock and moved to the Rifle Factory at Ishapore, Calcutta, to work when the post-World War I depression hit the UK. In 1925 the family resettled in Enfield, but 10 years later his parents and the two boys returned to Ishapore and the two girls remained in the UK to continue their education under grandparental guidance. In India Alec and his brother attended St Joseph's College, North Point, a boarding school in Darjeeling. The scenic Himalayan environment there stimulated a lifelong empathy with mountains, wild and remote environments, and most importantly, rocks and geology.

Returning to the UK in 1937 he completed secondary education at Luton Grammar School, where his enthusiasm for geology was reinforced and encouraged by his geography master. In 1946 Alec won a Royal Scholarship to the Imperial College of Science and Technology in London, where he graduated BSc (Hons), ARCS in 1949.

Imperial College was a stimulating place to be. H H Read (the respected international figurehead of the 'granitisation' movement) was head of the department; John Sutton and Janet Watson were working on their PhDs on the Lewisian rocks of Scotland; the structural geologist Wally Pitcher was a demonstrator. But the person who was to have the greatest influence on Alec's career was Robert Shackleton, who arrived fresh from mapping in Fiji in 1948 to teach a unit in petrology—although the essential message of this course was that the best way to understand the Earth was to get out into the field, make good maps, study the rocks in as much detail as possible, and interpret the evidence on its own merits, rather than rely on received opinion. Shackleton supervised Alec's Honours thesis, which involved the complete remapping of Achill Island, off the west coast of County Mayo.

In 1949 Robert Shackleton was appointed Professor of Geology at the University of Liverpool, and invited Alec to join him as a PhD student: Alec jumped at the chance. His research topic was 'The origin of albite gneisses' in a belt of low-grade Dalradian metasedimentary rocks in the Scottish Highlands and Achill Island.

In early 1951 Duncan Carse wrote to Robert Shackleton—a distant cousin of the Antarctic explorer Sir Ernest Shackleton—asking whether he knew of any young geologist, such as a PhD student, who might volunteer to join a six-man expedition to South Georgia

that he was organising to survey this major sub-Antarctic island. Shackleton discussed Carse's letter with Alec who was instantly attracted by the opportunity: Carse and Alec met in London, appropriately on board Scott's ship 'Discovery'! So began Alec's association with South Georgia geology.

Carse led three South Georgia Surveys—1951-52, 1953-54 and 1955-56—that are documented in detail in Alec's book *'Putting South Georgia on the map'* published in 2011. Alec was a member of the first two expeditions. On the 1951-52 expedition, 'Alec...disappeared down a hole in the snow!'—actually a bergschrund—and sustained a severely dislocated left knee that necessitated his being sent back to England for specialist treatment. In Alec's own words, written 61 years after the event: 'The unknown time between falling into the hole and finally emerging at the top marked a dividing point in Alec's life. He had escaped death on the first day of January 1952 by a chance of probably one in billions (how can it be calculated?). He had gone down overconfident, naïve, and too quick to ignore the advice of others. Although he didn't know it, his experiences during the rest of 1952 were to leave him a different person.'

During his recuperation Carse asked whether he was interested in going to South Georgia for the 1952-53 season. Alec declined because: (i) his surgeons advised against strenuous use of his left leg for a year; (ii) he needed to write up not only his PhD thesis but also the results of the 1951-52 field work; (iii) he had been offered a lectureship at Keele University; and (iv) in hospital he had met Kathleen Waldon, a nurse who had played a major part in his rehabilitation, and who he planned to marry. However, South Georgia continued to call him and Alec accepted Carse's invitation to join the 1953-54 expedition while at Keele and sailed south just two months after his marriage.

Alec's geological work was published in two FIDS (Falkland Island Dependencies Survey) Scientific Reports, *The geology of South Georgia I and II*. The British Antarctic Survey (the successor to FIDS) subsequently published a detailed map of the island in 1987, the work involving 11 geologists over eight years. The accompanying text stated 'The memoir is dedicated to Alec Trendall, who showed us all the way', a testament to the detailed observations he had made on the two expeditions he took part in.

On his return from South Georgia, and after writing up his geological results, Alec joined the Geological Survey of Uganda (at that time one of the Colonial Geological Surveys) in 1954 as a field geologist. Most of his geological work was in the Karamoja District in northeast Uganda, a sparsely inhabited plateau of arid savannah about 1000 m above sea-level, part of the Mozambique Belt, with scattered Cenozoic volcanic mountains rising to 3000 m. Alec and his family lived in bush camps, first in tents and later with the luxury of a caravan. All three children, Jasper, Justin and Lucy, were born in Uganda. His field work in Uganda was published in a number of Geological Survey of Uganda Records and Reports as well as a much cited paper on laterite entitled *The formation of apparent peneplains by a process of combined lateritisation and surface wash* published in Zeitschrift für Geomorphologie in 1962.

With Uganda independence looming Alec sought new pastures and accepted a position with the Geological Survey of Western Australia (GSWA) as petrologist, moving to Perth with the family in May 1962. He had little idea that the banded iron-formations (BIFs) of the Hamersley Group were to become a consuming interest for the rest of his geological career. This interest grew out of an investigation into the blue asbestos (crocidolite) occurrence in the BIFs of the group in which he was the lead researcher from 1964. It rapidly became apparent that a study of the origin of the BIFs was an important part of this investigation, particularly as these rocks are the primary source of the iron ore deposits that were being actively explored and developed at that time. This work culminated in GSWA Bulletin 119 *The iron formations of the Precambrian Hamersley Group, Western Australia, with special reference to the associated crocidolite* co-authored with John Blockley.

In pursuing his investigations into BIF Alec made many trips abroad to study similar deposits in South Africa, North America, Europe, India and Brazil. His 1968 paper, *Three great basins of Precambrian banded iron formation deposition: a systematic comparison* (published in the Geological Society of America Bulletin) was a summary of the first study tour. Alec considered that the microbanding in the BIFs were chemical evaporitic varves and in 1969 he applied for and received a Churchill Fellowship that enabled him to further develop a global context for the geology of the BIFs. One of the results from the trip was his 1971 Presidential Address to the Geological Society of Australia entitled *Revolution in earth history*, where 'revolution' referred to the annual journey of the Earth around the Sun—a typical 'trendallism'!

Alec received world-wide recognition for his work on BIFs and was invited to participate in one of the Dahlem Conferences organised by the Freie Universität in Berlin. The proceedings of this 1983 conference were subsequently published with a joint editorship of H D Holland and A F Trendall under the title *Patterns of Change in Earth Evolution*. He contributed to and jointly edited (with R C Morris) a book in Elsevier's Developments in Precambrian Geology series.

Alec recognised that work on the Precambrian rocks of Western Australia depended on accurate geochronological data. He had long been of the opinion that a numerical nomenclature for the Precambrian would enable Precambrian stratigraphy to 'start anew', rather than follow the approach used in the Phanerozoic. He articulated this in his 1966 paper *Towards rationalism in Precambrian stratigraphy* (published in the Journal of the Geological Society of Australia). In 1968 he and John De Laeter [head of Applied Physics at the Western Australian Institute of Technology (WAIT), now Curtin University] established a joint program whereby GSWA supplied the samples and WAIT did the analyses using, initially, the Rb–Sr technique. Well-defined problems were selected and the resulting papers were published mainly in the GSWA Annual Reports. Over the years other techniques were added. One interesting outcome of this work was the dating of the 'oldest rocks' in the Mt Narryer and Jack Hills regions—summarised in De Laeter and Trendall's 2002 paper *The oldest rocks: the Western Australian connection*, published in the Journal of the Royal Society of Western Australia.

Alec was appointed Deputy Director of GSWA in 1970 and was Director from 1980 to 1986. In 1986 he took the unusual decision to step down as Director to become a Principal Geologist and concentrate on geological research. This resulted in GSWA Report 42 *The Woongarra Rhyolite—a giant lavalike felsic sheet in the Hamersley Basin of Western Australia* published in 1995 and GSWA Bulletin 144 *Geology of the Fortescue Group, Pilbara Craton, Western Australia* co-authored with Alan Thorne and published in 2001.

One initiative during his term as director was to produce an updated account of the geology and mineral resources of the State. This was a large task and was uncompleted when Alec retired. However, his successor as Director, Phil Playford, gave Alec the task of overseeing the completion of what became Memoir 3 *Geology and mineral resources of Western Australia*, which was published in 1990 along with a new State geological map.

Alec was active in a number of scientific societies: Secretary of the Western Australian Division of the Geological Society of Australia from 1963 to 1965 and President from 1969 to 1971; Editor of the Journal of the Royal Society of Western Australia from 1965 to 1969 and President from 1973 to 1974; Chair of the Perth Branch of the Australasian Institute of Mining and Metallurgy in 1980 and Chair of the Organising Committee of the Perth Conference in 1979. He was also a Fellow of the Geological Society of London and the Geological Society of America.

After retirement in 1990 he continued his geological work, particularly in geochronology, and was an Adjunct Professor in the Applied Physics Department at Curtin University, continuing his collaboration with John De Laeter. This culminated in the multi-authored *SHRIMP zircon ages constraining the depositional chronology of the Hamersley Group, Western Australia* published in the Australian Journal of Earth Sciences in 2004. He crystallised his ideas on the origin of the continents in a 1996 paper *A tale of two cratons: speculations on the origin of continents* published in the Royal Society of Western Australia's De Laeter Symposium volume.

He was eventually able to return to the place and time that stimulated his interest in geology when he was offered the chance to write an account of Duncan Carse's expeditions to South Georgia. In 2007 he was fortunate to be able to travel to South Georgia to commemorate Duncan Carse's achievements. The changes between his first visit in 1951 and his last in 2007 are implicit in the title of an SBS documentary of the trip: Antarctica–the Great Meltdown. His book was privately published in 2011 under the title *Putting South Georgia on the Map*.

Alec received many honours in recognition of his contributions to geology. He was awarded a DSc for his work on BIFs by the University of London, the Clarke Medal of the Royal Society of New South Wales in 1977 and the Gibb Maitland Medal by the Western Australian Division of the Geological Society of Australia in 1987. Trendall Crag in South Georgia is named after him.

Alec always maintained an interest in languages, including Mandarin Chinese and Russian. He was sufficiently fluent in Russian to be able to deliver a geological paper in that language at an International Symposium in Kiev. An accomplished keyboard player he carried a clavichord (the smallest keyboard he could find, but still not really portable) into the field in Uganda and subsequently built a spinet, a harpischord (his son Justin painted the sound board) and a forte piano from kit sets. I was privileged to hear him play the harpsichord; the beautiful sound from it a tribute to his skill, not only as a player but also as a builder.

In 1995 Alec and Kath moved to Springhaven a property near Denmark on the south coast where they planted fruit trees, oak trees and banksias and ran a small herd of goats. Here he added cheese making to his many interests and I believe perfected a local version of the traditional ash-coated pyramid. Sadly I never tasted his goat cheese.

Truly a man of many talents. We shall not see his like again.

Alec Francis Trendall BSc (Hons) (London), ARCS, PhD (Liverpool), DSc (London), DSc (hc) (Curtin): 8 December 1928—4 April 2013

(Tony Cockbain, based on an auto-obituary started in Albany Hospital on 19 January 2013, supplemented by details from his book 'Putting South Georgia on the map', with assistance from Kathleen and Jasper Trendall, and John Blockley)

Editor's note

PUBLICATION DATES OF JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA VOL. 95, 2012

The publication dates given on the cover of each issue of the journal are indicative rather than actual publication dates. The printed issues were published on the following dates:

95 (1) pp. 1–76	20 May 2012
95 (2) pp. 77–124	5 September 2012
95 (3,4) pp. 125–176	28 December 2012

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✉ rswa@museum.wa.gov.au
ISSN 0035-922X Print Post Approved PP642409/00008.

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Typeset and printed in Western Australia